RETURN TO H. W. HOWARD

ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

VOLUME 60, ART. 6 PAGES 807–964

RECEIVED
JUN 2 1955
H. W. H.

Editor
ROY WALDO MINER

INSTRUMENTATION

BY

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NEW YORK
PUBLISHED BY THE ACADEMY
April 30, 1955

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(Founded in 1817)

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ANNALS OF THE NEW YORK ACADEMY OF SCIENCES
VOLUME 60, ART. 6 PAGES 807–964
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ROY WALDO MINER

INSTRUMENTATION*

Conference Chairman and Consulting Editor

JOSEPH GREENSPAN

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* This series of papers is the result of a conference on *Instrumentation* held by the Section of Biology of The New York Academy of Sciences, October 28 and 29, 1954.

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Part I. The Science of Instrumentation

INSTRUMENTATION RESEARCH AT THE NATIONAL BUREAU OF STANDARDS

By William A. Wildhack

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Just prior to the establishment of the National Bureau of Standards, the situation in regard to standards of physical measurement in the United States was characterized by the National Academy of Sciences in these words: "The facilities at the disposal of the government and of the scientific men of the country for the standardization of apparatus used in scientific research and in the arts are now either absent or entirely inadequate, so that it becomes necessary to send such apparatus abroad for comparison." The following year, 1901, in response to the urging of leading scientists, the National Bureau of Standards came into being as the primary agency of the government for the maintenance and development of physical standards and, since then, has played a leading role in the fundamental research of this country.

As authorized by Act of Congress, the Bureau has six broad functions: (1) the custody, maintenance, and development of national standards of measurement and related measurement problems; (2) the determination of physical constants and properties of materials; (3) the testing and the development of methods for testing materials, mechanisms, and structures; (4) cooperative activities relating to standard practices incorporated in codes and specifications; (5) advisory services to Government agencies on scientific and technical problems; and (6) the development of devices to serve special needs of the Government. It is in support of these broad functions that instrumentation research at the National Bureau of Standards is undertaken.

Currently the work of the Bureau is carried on by sixteen technical divisions (see TABLE 1). The work of the technical divisions is supplemented by the Office of Weights and Measures, providing liaison between the Bureau and state and local weights and measures organizations, and by the Office of Basic Instrumentation, of which more later. *The Technical News Bulletin*, a monthly publication of the National Bureau of Standards, is a useful source of information on current activities of the Bureau.

It may not appear obvious that an organization so explicitly dedicated to furthering the needs of the physical sciences would make any significant contributions to the biological sciences. But it is characteristic of science in general that traditional barriers between fields are not impenetrable. Techniques and instrumentation developed in one field often find valuable applications in other fields.

Workers in the field of medical physics, for example, have sought the assistance of the National Bureau of Standards in pursuing a variety of research activities. A few of them may be listed: (1) maintenance of standards for acoustics and calibration of audiometers; (2) investigation of the mechanical

TABLE 1

DIVISIONS OF THE NATIONAL BUREAU OF STANDARDS

(1)	Electricity and electronics	(9)	Mineral products
(2)	Optics and metrology	(10)	Building technology
(3)	Heat and power	(11)	Applied mathematics
(4)	Atomic and radiation physics	(12)	Data processing systems
(5)	Chemistry	(81)	Cryogenic engineering
(6)	Mechanics	(82)	Radio propagation physics
(7)	Organic and fibrous materials	(83)	Radio propagation engineering
(8)	Metallurgy	(84)	Radio standards

properties of bones, artificial limbs, and connecting screws; (3) development of special accelerometers in conjunction with military projects on ejection seats and high-speed maneuvering of aircraft; (4) evaluation and development of oxygen breathing instruments, masks, pressure suits, *etc.*; (5) blood-pressure measuring instruments—performance limitations of mercurial and aneroid types; (6) testing of plastic heart valves under simulated flow conditions; (7) anesthesia monitoring instrument; (8) dental research—physical and chemical properties of materials; (9) radiation measuring instruments, standards, and protection; (10) explosion hazards in operating rooms; and (11) testing, evaluation, and preparation of specifications for a variety of items, including sutures, surgeon's gloves, diagnostic tubes, adhesive plaster, clinical thermometers, hemocytometers, pipettes and other volumetric apparatus, and electromedical equipment.

This work has generally been undertaken by the Bureau as part of its service to other agencies of the government or in cooperation with professional societies such as the American Dental Association.

The Bureau makes its contributions on these projects through the application of its special knowledge and facilities in the field of the physical sciences. It does not attempt to pass judgment on the significance of the developments from the standpoint of medical applications.

Oxygen Requirements

An interesting example of the cooperation that exists between the physical scientists and their colleagues in physiology is presented by a study the author made, early in the war, on oxygen requirements at high altitudes.[1]

Experience had shown that normal persons, when breathing air, suffered a marked loss of efficiency somewhere in the range from 10,000 to 15,000 feet and would collapse at about 20,000 feet. On the other hand, breathing supplemental oxygen, normal persons could ascend to much greater altitudes without danger of collapse.

The equipment then available to provide the supplemental oxygen, although crude, seemed adequate in limited use tests, but there were no standards by which to judge its performance and no certain basis for defining what the performance should be. An important question, to which there was no detailed experimental answer, was: What percentages of oxygen are required in the inspired air at various altitudes to maintain an oxygen pressure deep in the lungs equivalent to that obtained with a given oxygen percentage at a given altitude?

Taking into account the partial pressures of water vapor and carbon dioxide and the approximate variation of the pressure of carbon dioxide with alveolar oxygen pressure, the author developed theoretical equations for the oxygen concentration to be breathed at any altitude to maintain this "oxygen equivalent" of air at given altitude. On this basis, performance specifications were drawn to guide the instrument designers and manufacturers in producing the dilutor-type oxygen regulators which have become the standard equipment, and to permit quantitative testing and checking of the regulators.

An interesting sidelight indicating where the physical scientist leaves off and the biological scientist takes over is the fact that Air Force physiologists selected the sea-level oxygen equivalent as the one appropriate for high-altitude flight. The Navy, on advice of its physiologists, ruled that its regulators should be adjusted to provide a below-sea level equivalent in the altitude range 20,000 to 33,000 feet!

After Air Force physiologists found that the altitude tolerance could be temporarily increased by breathing pure oxygen under a slight positive pressure, the author designed a pressure-compensated or "balanced" exhaust valve for an oxygen mask. This device made it practical to utilize "pressure breathing"—the supercharging of the lungs of the aviator—by allowing the expired breath to escape without permitting leakage during other parts of the breathing cycle. The pressure-compensated valve was designed so that it would normally stay closed when the pressures in a pressure cell on one side and in the breathing tube or mask on the other side were equal, but would open when the mask pressure exceeded the cell pressure, as in exhaling.

The instruments developed in relation to the Bureau's activities connected with medical research are part of the large family of instruments generated by the Bureau over the years in maintenance of its basic functions. Nevertheless, the Bureau has been a Spartan parent to many of its instrument offspring. Many promising new instrument ideas have been discarded because they did not fall directly within the scope of a particular research program or because funds and personnel could not be diverted to their exploration. Often such ideas, although they seemed to have only secondary importance to the project which evolved them, have had great potential value for other work of the Bureau. With the growth in the complexity of present-day instrumentation at the Bureau (as elsewhere) the need has grown for an organization that could cut across organizational lines, give recognition to improvements or innovations wherever they appeared, and give the necessary financial support to promising instrumentation projects.

Basic Instrumentation Program

It was proposed, in 1949, that a program of basic instrumentation research and development be instituted at the Bureau in cooperation with the Department of Defense and the Atomic Energy Commission. This program would be pursued in a manner to bring into play, on basic instrumentation problems, the ideas and developments originating in all technical fields, to an extent possible only in a coordinated program of broad scope.

In general, the focus of the program was intended to be placed on the definition and solution of problems common to broad areas of measurement and control. Specifically, it was proposed to undertake: (1) surveys—*i.e.*, systematic and comprehensive analyses of available methods and devices for laboratory and field measurements of physical magnitudes; and (2) laboratory research on new applications of principles and materials leading to the development of instruments and techniques not now available.

In July 1950, the Office of Basic Instrumentation (OBI) of the National Bureau of Standards was established with the responsibility of coordinating and administering a Bureau-wide program of research and development in instrumentation. It was particularly designed to cut across traditional division lines at the Bureau. OBI was also to serve as a research, reference, and consultation center on problems of instrumentation for government agencies and their contractors. Organizationally, OBI itself has always been small—small in numbers and in its own facilities—but, in carrying out its program, it draws upon the entire Bureau staff and facilities.

It is the policy of OBI to draw upon the competence of the existing divisions of the Bureau wherever possible. In cases where there seems to be the need to perform limited explorations in new fields not covered by the program of existing divisions, OBI undertakes to carry out the initial studies in its own laboratory with its own personnel. In addition to the laboratory groups, a group of specialists in OBI provides reference and consultation services to aid in the solution of instrumentation problems.

OBI projects originate in several ways. The sponsoring agencies, namely the Air Force, the Office of Naval Research, and the Atomic Energy Commission, suggest specific problems that they would like to see investigated. Certain divisions of the Bureau propose instrument investigations in connection with existing projects, and OBI recommends particular fields for further investigation by the various technical divisions.

Representative Projects

In the following sections, several representative projects are discussed briefly to show the scope and diversity of the OBI program.

OBI surveys. Surveys of some interest to the biological field have been prepared on: millimicrosecond oscillography; analog-to-digital computers; respiratory gas analysis.

New oscillographs capable of measuring events that occur in a fraction of a microsecond are gaining importance in such diverse applications as atomic and nuclear physics, study of electrical breakdowns, and communications systems.

In the new era of high speed computers, there has been increasing emphasis on means of converting analog voltages to digital forms suitable for feeding into digital computers. An increasing number of such devices is now commercially available. OBI's survey has provided comprehensive information on the requirements of such devices and on techniques presently being used to meet them.

The survey of methods of respiratory analysis, conducted by Doctor H. J. Morowitz as one part of a group of projects on medical physics instrumentation, may be of interest to many members of the Section on Biology of The New York Academy of Sciences. In this survey, the existing methods of respiratory gas analysis were examined, compared on various points of performance, such as accuracy, response time, sampling time, or testing time, *etc.*, and other physical instruments and techniques were studied for possible applicability. A table, listing and comparing 30 techniques applicable to respiratory gas analysis, was prepared, and recommendations were made as to methods which appeared to offer the most promise or to merit further basic study. Two instruments developed at the Bureau, the radio-frequency-mass spectrometer and the critical-flow-gas analyzer, appeared to show promise in such respiratory work. The critical-flow-gas analyzer is described in the next section. Some of OBI's activities in research and development and the OBI reference service are described in the following sections.

Measurement of flow. Several projects at the National Bureau of Standards have been concerned with the development of instruments to measure the flow of fluids. The linear flowmeter was developed particularly for use in respiratory studies and in testing oxygen equipment. The acoustic flowmeter has been used in the nonobstructive measurement of the flow of blood. These devices and others for the measurement of flow are summarized in a review article which appeared in *Science* recently.[2]

The phenomenon known as critical flow has been applied to the design of a "critical-flow-gas analyzer."[3] Critical flow occurs when a gas is flowing through a rounded nozzle under conditions such that the absolute pressure in the throat is less than about half the absolute pressure at the inlet. Under these conditions, the gas velocity at the throat of the nozzle is equal to the velocity of sound, and the volume flow is independent of the downstream pressure. Then, when temperature is held constant, the mass flow of the gas is proportional to the entrance pressure.

In the critical-flow-gas analyzer, four nozzles are arranged in two parallel circuits, analogous to a Wheatstone bridge (FIGURE 1). The gas mixture is passed through some agent such as a liquid air trap, chemical bubbler, a saturator, or a canister of desiccant or other reagent to remove or modify one of the components of the mixture. The resultant difference in the entrance pressures at the two downstream nozzles, ΔP_2, is indicated by a differential manometer and can be calibrated in terms of the amount of a particular constituent that has been removed from the gas.

Instrument reference center. The Office of Basic Instrumentation has recognized the unique information requirements of the field of instrumentation. Because instrumentation is the common denominator of all the other branches of science and technology, the publications of all these branches are sources of instrument information. Only a small fraction of instrument developments are reported in journals such as *The Review of Scientific Instruments* and *The*

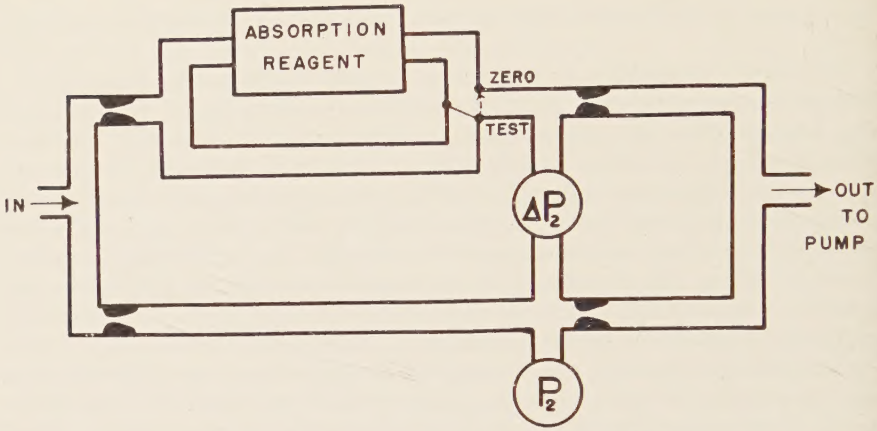

FIGURE 1. Schematic drawing of critical-flow-gas analyzer.

Journal of Scientific Instruments, which are devoted specifically to instrumentation. Therefore, it was decided that an instrument reference center would be established at OBI to serve as a clearing house for instrument information. A "multidimensional" classification system has been adopted to process instrument information so that it is possible to index and search for information according to certain categories or points of view, such as: measurand, principle of operation, object on which measurement is made, field of application, *etc.*

A mechanical punched-card system (christened "Peek-a-Boo" at the Bureau, though not conceived there) has been adopted as a convenient mechanical aid to search. At present, the system is still in the experimental stage, but we are starting to index the current instrument information from the most important of the journals providing such information.

In this Peek-a-Boo system, as used by OBI, there is one card for each descriptive term to be indexed. These "subject" cards are filed alphabetically within each category. Each document that is indexed is assigned a serial number. A hole is punched on each appropriate subject card at a position corresponding to the serial number. In making a search, the desired subject cards are laid one on top of another and viewed against a light. Where there is a "hit," the light shines through all the cards and the serial number of the reference is determined by the location of the hole. FIGURE 2 illustrates this search principle. The first card may be imagined to be labelled "blood" (the object on which measurement is made). Suppose the second card is labelled "flow" (the condition being measured). Then the two places where the holes are coincident (the beam passing straight through) represent two documents on the flow of blood.

Shock and vibration measurements. Several groups at the National Bureau of Standards are working on the measurement of shock and vibration. One development, the Ramberg vacuum tube accelerometer, is essentially a double diode with elastically supported plates on either side of a common cathode. Acceleration of the base in the sensitive direction causes a relative displacement

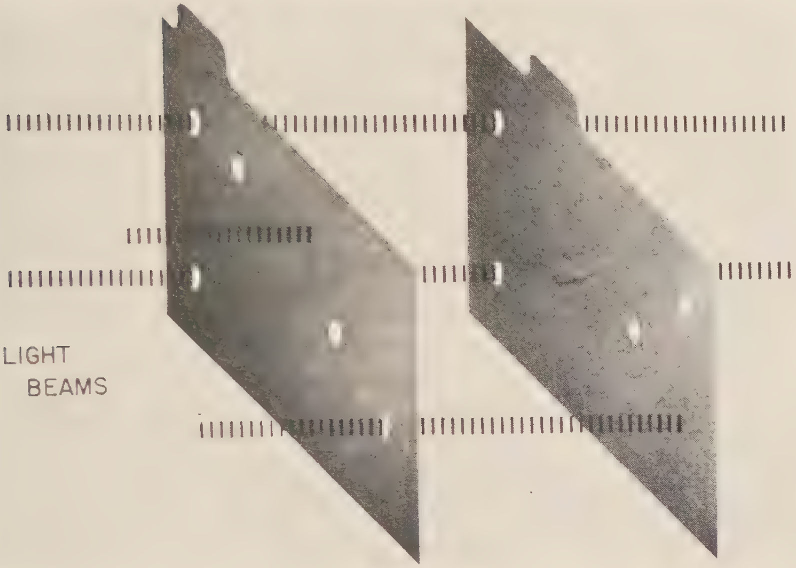

Figure 2. The Peek-a-Boo principle.

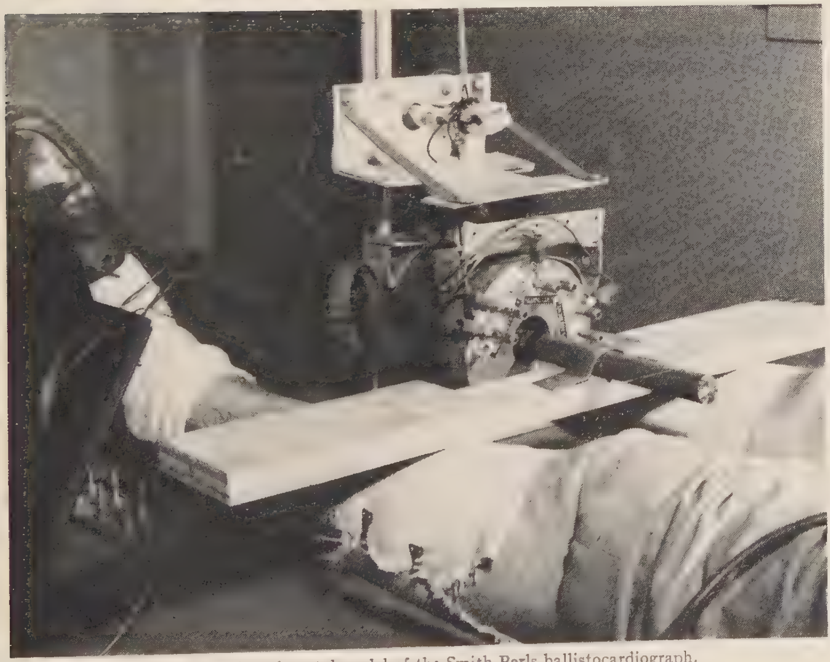

Figure 3. Experimental model of the Smith-Perls ballistocardiograph.

between the plates and the cathode. The change in plate-to-cathode resistance is a measure of the acceleration.

More recent accelerometers use piezoelectric barium titanate crystals as the sensing element. The NBS 33-14 barium titanate accelerometer combines exceptionally wide frequency and acceleration ranges (2 20,000 cps. ± 30,000 g.) with small size, low mass, uniformity of response, and a sensitivity of about 1 millivolt per "g."

An interesting physiological application of an instrument designed for general vibration and shock measurements is the integrating and differentiating bar-magnet velocity meter for use in ballistocardiography. The bar-magnet velocity meter incorporates the principle taught in elementary physics that, if a bar magnet is thrust into a coil of wire, a voltage is generated which is proportional to the speed of the bar magnet relative to the coil.

In using the instrument, the patient lies on a table made as free as possible of extraneous vibration. FIGURE 3 illustrates the installation at the Medical Standards Laboratory of the Civil Aeronautics Administration designed by Doctor J. E. Smith.[4] The coil is fixed relative to the table, while the magnet is fastened to a wooden platform which rests across the patient's shins.

This instrument has several advantages over devices previously used in ballistocardiography: its sensitivity is independent, over a wide range, of the relative position and angle of its elements, and it provides an electrical output proportional to velocity and of sufficient magnitude to allow simultaneous integration and differentiation in passive networks with sufficient output to drive standard recorders now in general use for both ballistocardiography and electrocardiography.

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MEDICAL RESEARCH INSTRUMENTATION

By Robert L. Bowman

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It appears obvious that more and better instrumentation, properly applied, can increase the efficiency of many phases of medical research. I should like to confine my remarks to instrumentation in the research field without meaning to imply that the practice of medicine and surgery could not profit by the same application. However, medical research instrumentation comes first. The techniques will be applied to medical practice when their value has been established in the research application.

In medical circles, the word "instrument" generally suggests a tool used in some internal manipulation or inspection. I prefer to include these devices under instruments, as their development is just as important and involves the same skills and materials as instrumentation in general.

It would appear, at first glance, that the medical sciences or, more broadly, the biological sciences, could be advised of the multitude of excellent instruments available to industry today and that these instruments, with minor modification, would solve their problems. This statement is true to a small extent, but most of the problems are on such a different scale, and the difficulties of measuring without influencing the measurement so great that these instruments frequently create more problems than they solve.

There are, therefore, two problems: better utilization of instruments already developed, and the development of special biological instruments.

The skills and materials of modern physical science could be better utilized by the medical research scientist than they are at present. Instrumentation can now assist research in so many ways that, to utilize the possibilities adequately, one must learn a great deal about instruments or rely on the knowledge of experts to apply them adequately.

Even the nuclear physicist today has to rely on others to instrument for him, for some of his machines are now too complex for a single man to build or even operate. He relies on instrument experts to lighten his task of instrumenting. The biological worker also needs help in this respect but often on a very different level. His problems may be at the level of selecting the proper galvanometer for a simple Wheatstone bridge circuit.

Not all medical research workers are in this class, however, so let us, for convenience, divide them into three classes and consider their problems separately.

One type is the trained biologist having no training in the physical sciences, who is reluctant to tackle any physical problem; another type is the biophysicist who has formal training in both fields; and the third type is the trained biologist who has only informal training and some experience in instrumentation and its physical foundations. It is apparent that these types characterize peaks in a more continuous spectrum of individuals.

The biologist who has neither knowledge nor interest in the physical basis of instruments cannot expect to obtain the maximum in dependable service if he relies on published step-by-step instructions or words of advice from colleagues who, he believes, are able to advise him on the use of his instruments. He wants dependable data and no bother in the form of servicing requirements, and so he delegates adjustments and repairs to paid service men. In addition, he refers such "interesting" problems as instability due to poor battery clips to any sympathetic engineer, physicist, or "instrumentologist," not realizing that this type of work, to an engineer, is just as much something he understands and can handle as cleaning dried blood out of a long-necked flask is to a biochemist. The engineer certainly knows how to handle the problem, but does not look forward to such tasks. In this same category of problems are frayed line cords, poor grounds, moisture on electrometer tubes, mice and other vermin inside amplifiers, and the like.

It seems clear to me that such an individual should learn more about his instruments or suffer the consequences. With the use of an instrument, there is a certain responsibility on the part of the user if he is to utilize it effectively, or he will always be faced with the possibility that the instrument will not answer the questions he is asking of it.

The biophysicist, on the other hand, is trained in both fields and is generally competent, not only to utilize complex instruments, but to appreciate the possibilities of developing new ones. He uses available instruments competently, maintains them in calibration, and performs or supervises the performance of minor servicing. He is interested in the instrumentologist as a colleague with whom he can explore the possibilities of instrumenting some new idea, or with whom he can collaborate in its development. He speaks the physicists' language and interests them in the problem of biological systems and, at times, he may even influence some of them to become biophysicists themselves.

The third group constitutes those biologists and medical scientists who are eager to interpret biological phenomena in the light of physical principles and to apply the instruments necessary to obtain adequate data.

This type of investigator generally knows the physics and instrumentation of his specific field quite well, but lacks the broad base and perspective of the trained physicist, engineer, or instrumentologist. Generally, he is aware of his narrow viewpoint and wants expert advice and assistance in the utilization of present instruments, as well as collaboration in the instrumentation of some specific need.

At present, this type of investigator handles these problems by studying such subjects as hydraulics, mechanics, electronics, and nucleonics until he can handle his own problem with the assistance of consultants and with the temporary employment of specialized technicians. He frequently presents physicists or instrumentologists who may be consultants, friends, or acquaintances with problems so interesting to them that they contribute a great deal of part-time effort to the project, and frequently are remunerated only by their feeling that they have contributed something to medical progress. Not infrequently, the actual construction of the final apparatus is performed by an engineering firm with the usual, though understandable, inflexibility of a contract in which modifications during construction are permitted only with penalty costs.

As the application of instruments and materials progresses at a slow rate, a desire to commercialize research equipment in order to defray large development costs encourages some of the contractors to sell a few reproductions of the instrument, once the problems involved are solved. This procedure often results in the application of a complex specialized piece of research equipment to some minor problem that could be handled more economically with a simpler instrument.

By having instrumentologists attached to a problem only on consultation or part-time basis, their skills are not utilized most effectively. Also, their participation is on such a superficial level that they are easily attracted elsewhere.

There are so many challenging problems for the instrumentologist, in association with those in the last two groups, that some means of incorporating such an individual into the working team is most likely to be rewarding. This individual must, however, join the group as a fellow scientist and collaborator if he is to be stimulated to do his best work.

Biophysics groups could easily add instrumentologists without seriously changing the character of their facilities, and they could profit by the association.

The best instrumentologists are probably like the best biophysicists—they will collaborate, but they also like to have their own research problem. A good methodologist, accordingly, can be attracted only if he is given the status and prestige of the scientist and is encouraged to do instrumentation and methodology, research, and development, in the sense of pure research. One must not insist on a use for all the methods he develops. As in pure science, the unexpected is often the most valuable.

THE RELATIONSHIP BETWEEN THE PROCESS OF MEASUREMENT AND INSTRUMENTATION IN BIOLOGY

By Harold J. Morowitz

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Introduction

> Without accurate measurements physics and chemistry would never have developed. But the significance of these measurements lies in their relation to new concepts and conceptual schemes, and above all in the way the numerical results may be manipulated by logical processes.
>
> —J. B. Conant.

The success of precise quantitative measurement in the physical sciences has prompted many biological research workers to attempt quantitative measurements in their respective disciplines. A growing number of investigators are engaged in an attempt to analyze complex biological phenomena in terms of the simpler laws of physics and chemistry. This trend toward physical theory has been accompanied by an ever-increasing use, by biologists, of instruments and measuring techniques originally developed for other purposes.

The application of quantitative measurement to biology, however, has not always met with complete success. Frequently the precise data, once obtained, throw no more light on the situation under study than the previous crude qualitative data. The precise instrument alone, in many cases, has been insufficient in the elucidation of problems. In other instances, it is difficult to determine what is actually being measured. These points make it apparent that the "theory of biological instrumentation" must relate itself to the general philosophy of biological measurement.

While it is not our purpose to intrude on the domain of the philosopher, the following questions seem pertinent in setting forth and evaluating biological instrumentation: (1) what questions are being asked about biological systems? (2) what types of information will provide answers to these questions? (3) what types of observations and measurements will provide this information?

Without trying to detail the answers to these questions, but keeping the questions in mind, we shall attempt to analyze biological measurements to see what is being measured, how the results of measurements are used, what constitute the fundamental limitations of measurement and, ultimately, what effect these factors have on biological instrumentation. We shall adopt the operational point of view in dealing with the measurement process.

Comparison of Physical and Biological Measurements

> We do not know the meaning of a concept unless we can specify the operations which were used by us or our neighbor in applying the concept to any concrete situation.
>
> —P. Bridgeman.

We shall begin our analysis by comparing biological measurements with simple physical measurements. At the outset, we shall postulate that the measurement processes are qualitatively the same but differ due to quantitative differences imposed by the greater complexity of biological systems. A simple example will illustrate this point. Suppose we wish to measure the length of two objects, a gold bar and an earthworm. We shall employ the same set of operations to compare the lengths with some fixed standards. We find that the gold bar does not have a unique length unless we also specify the temperature. The earthworm provides a more difficult problem, for our measurement is constantly changing. No matter how many of the external variables we control and measure, we cannot measure a length that is unique and reproducible. The difference between the two measurements is qualitative in the sense that a sufficiently refined measurement of the gold bar would reveal changes in length that seemed as arbitrary as those of the earthworm. These changes might result from random thermal motion and stray electromagnetic or gravitational fields. The difference is that, in simple physical measurements, we are usually able to control parameters which affect the measurement to the degree of precision at which we wish to operate. In the tremendously complicated biological system we are frequently unable so to control the system.

In each case, we might employ statistical analysis to specify the length but, employing the same instruments and methods, the two sets of determinations would have radically different variances. Since we have employed the same operations and have obtained different types of results, we must conclude that the concept "length" is somewhat different when applied to a gold bar than when applied to an earthworm.

The previous example may be summed up formally as follows: A simple physical measurement rarely involves a single set of operations to determine a single variable, but it implies control (hence measurement) of other variables which influence the variable which one desires to measure. In general, the number of other variables is large but, in simple physical measurements, only a few of them influence the original measurement enough to be detectable within the desired degree of precision. The extreme case is classical thermodynamics where "the state of single substance is found to be completely determined by any two of the three quantities p, v, T."[1]

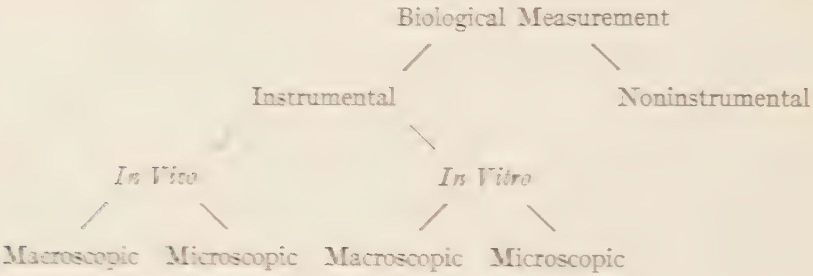
A biological measurement, on the other hand, is influenced by a large number of factors only a few of which can be known, measured, or controlled in a given experiment. The biological measurement will have a greater variance even in those cases where the same instrument is employed.

It must be realized that the physicist generally works with systems which are more complex than the measurement of the length of a gold bar and, in fact, the more complex the system he works with, the more likely he is to encounter problems similar to those of the biologist.

Biological Measurement

> However these problems are in general so complex that only an empirical approach is possible. Theoretical interpretations are often hindered by the fact that there are too many variables. As a matter of fact, constants as used in physical experiments do not exist.
>
> —A. Frey-Wyssling.

For the purpose of discussion, we shall divide biological measurements into the categories shown in the following chart:



Noninstrumental Measurement

The noninstrumental type of measurement has some interesting features, many of which seem unique to biology. The basic measurement involves looking at an object or set of objects and counting. It will be shown by example that such measurements can lead to a formal mathematical science. The success of such measurements and the disciplines they engender seems to depend on the all-or-none character of certain biological phenomena.

Consider, first, classical Mendelian genetics. Here the essential measurement is a visual examination and count of phenotypes. Frequently, unit all-or-none phenotypic characters such as red eye-color and white eye-color can be employed. No measuring instruments, with the exception of the observer's eye, are used; no standards are employed; and yet a complex formal science has evolved which is, by and large, successful in predicting the hereditary transmission of phenotypes.

Next, consider the sensitivity of microorganisms to ionizing radiation. An organism is judged to be alive if it will form a visible colony on suitable nutrient agar, and dead if it fails to do so. A large number of organisms are irradiated in aliquots, each aliquot receiving a different dose of radiation (instruments, of course, play a large part in determining the quantitative value of this dose). The aliquots are then plated on nutrient agar and allowed to grow. The number of visible colonies from each aliquot is counted, and a dose-survival curve is plotted. Such experiments lead to a detailed discipline yielding radiation cross-sections, information on ploidy, and other pertinent information about the cell. Here, again, the basic measurement is a visual examination and count.

In the case of radiation, the organism itself acts somewhat as the instrument of detection. The microorganism is a sensing element for the radiation damage induced. The surviving organisms act as amplifiers with an amplification of about 10^8. The critically damaged organisms, in general, amplify less than 10^4 and are not counted as visible colonies. Here, we again see an all-or-none phenomenon, two classes of organisms sharply differentiated in their ability to reproduce.

The radiation experiment provides an example of the "black box" approach to biological measurement. This methodology involves no direct measurement of the organism itself; *i.e.*, no sensing probe brought into contact with the organism. The experimenter acts upon a population of organisms with some quantitatively defined factor and observes the results. This method is not unique to biology. Physics often deals with submicroscopic particles in the same way in such experiments as determining nuclear scattering cross-sections. The science then proceeds by postulating the type of black box that can account for the observed results.

Instrumental in Vitro *Measurement*

The category of instrumental *in vitro* measurements includes those biochemical and cytological experiments in which the organism is killed and/or fractionated or otherwise treated, as well as those experiments in which material is withdrawn from the organism and treated and analyzed. Measurements on material so treated are complicated by the fact that one must relate the observable to a corresponding physical situation in the organism prior to treatment. Numerous difficulties have arisen in such procedures, and the term artifact has been applied to a class of observations which is characteristic of the method of preparation rather than the object of study.

The history of the material being studied is one of the variables of the system. In preparing the material, we subject it to many complex physical and chemical factors. That is to say, there is a series of uncontrolled and unmeasured variables. The interpretation of the final measurements rests upon the manner in which we treat the complex of unmeasured quantities.

In spite of these difficulties, great progress has been made in cytological and biochemical measurement. The disciplines, however, are inherently burdened with an uncertainty arising from the ill-defined process of going from an *in vivo* to an *in vitro* system.

At the microscopic level, another factor, that of thermal noise, serves as a further limitation. The limitations imposed by such factors in preparing materials have recently been discussed in some detail[2] and will not be elaborated at this point.

It seems pertinent, at this juncture, to inquire into the function of instrumentation in overcoming the basic difficulty of *in vitro* measurements. One possibility lies in performing measurements on materials that have undergone a minimum degree of preparation. This method is in the direction of transforming *in vitro* to *in vivo* measurements. For example, an instrument for determing molecular weights of proteins which did not require relatively pure samples would entail considerably less chemical manipulation of these rather unstable molecules.

In Vivo *Instrumental Measurements*

In vivo instrumental measurements include those experiments in which measurements are taken by a sensing element in contact with, or in proximity to, a living organism. Macroscopic measurements fall within the scope of physiology; microscopic measurements, within the field of cellular physiology.

In vivo measurements, in addition to being complicated by the usual array of unmeasured variables, must deal with the problems of the interaction of the sensing probe with organism, and the fact that it is usually not possible to isolate the area under study, since the organism acts as a very highly integrated unit.

Consider first the macroscopic case. Here the probe might consist of a thermometer, a catheter with appropriate sensing element, electrical contacts, or similar devices. In most cases, the probe will be in direct contact with the organism. Certain very important restrictions must be placed on the sensing probes for biological experiment.

(1) Probes measuring quantities, which can be represented by scalar or vector fields, must be small in comparison with dimensions in which an appreciable change of the field variable occurs.

(2) The perturbation of the scalar or vector field by the probe must be small in comparison to the quantity measured.

(3) The probe must cause a minimum of local trauma.

(4) The probe must cause a minimum of stimulation to the organism.

Two examples will demonstrate the probe-size restriction. Suppose one wishes to measure the electrical potential field over the surface of an organism. Suppose, further, that between two points a distance x apart, there is a difference of potential y. In order that y be measured with any precision, the probe size, P, must be regulated so that $\frac{Py}{x}$ is small in comparison with y. In a second example, suppose we wished to measure the flow velocity at a point in the blood stream, and suppose further that we were able to use some flow-sensing device on the end of a catheter. The sensing element and probe should then cause a negligible effect on the hydrodynamic velocity field. Here, again, a small probe is of importance.

The problem of local trauma is present whenever the sensing probe must be placed within the organism. The organism responds to this trauma in such a way that the measurement taken may be more characteristic of the traumatized organism than of the basic physiological variable under consideration. For instance, certain types of probes placed under the skin to measure skin temperature might produce considerable local irritation, flow of blood, and concomitant temperature rise. The recorded value of temperature is hardly a true measure of the unperturbed system.

The basic philosophical difficulty, however, persists in that we are able to say nothing about the value of a given measurable in a completely unperturbed system. Instead, we must work in the direction of perturbing the system as little as possible by interaction of the organism with a measuring instrument.

The third difficulty stems from the fact that responsiveness to stimuli is a characteristic of living organisms. As the response, in general, involves a much larger release of energy than the stimulus, the effect of the response on the attempted measurement might be very significant. The stimulus-response situation is characteristic of the integrated nature of the entire organism, and this fact tends to delocalize and diffuse a given measurement even further.

A whole class of physiological studies is bounded by two sets of stimuli:

either the organism is strapped to a laboratory table; or the organism is anesthetized. In each case, these accompanying variables are significant in interpreting the results.

In Vivo *Microscopic Measurements*

The probe requirements encountered in *in vivo* macroscopic measurements become even more exacting for cellular measurements, for the practical lower limit of probe size is of the same order of magnitude as the cells which one desires to study.

Again, let us consider an example to illustrate the difficulties one might encounter in this type of measurement. Consider the measurement of temperature inside of a cell two microns in diameter, using a copper-constantan thermocouple. In order to keep the probe size small in comparison with the cell size and reduce local trauma, wires of the order of a tenth of a micron diameter would have to be used. For such wires, there would be the problem of fabricating, placing, and localizing them in the cell, and the further problem of signal to noise ratio.

Assuming that the wires could be fabricated, let us consider localization from the point of view of Brownian motion. For two wires, each two microns in length, we shall calculate the square root of the mean square displacement of a sphere of equivalent volume. The mean square displacement Δ^2 is given by the following formula:

$$\Delta^2 = \frac{kTt}{3\pi\eta r}$$

where k is Boltzmann's constant, T the absolute temperature, t the time interval of observation, η the viscosity and r the radius of the sphere. The wires form an equivalent sphere of 0.3 micron radius, which would show the following mean Brownian displacement:

$$\sqrt{\Delta^2} = .52\sqrt{t} \text{ microns}$$

It is thus impossible to localize the probe over any reasonable time interval. It should also be noted that the wires employed are of such small size as to be near the limits of resolution of an optical microscope.

In dealing with the problem of signal to noise, let us consider the Johnson noise in the probe wires. This is given by

$$E^2 = 4kTR\Delta f$$

where E^2 is the mean square noise voltage, R the resistance and Δf the frequency range. The resistance of the thermocouple under consideration is about five ohms. For a frequency range of about 100 cycles $\sqrt{E^2}$ is about a mili microvolt. Since the thermoelectric power of a copper-constantan couple is the order of 40 microvolts per degree, a negligible error is to be anticipated from this source. The problem of distribution of static charges in the inhomogeneous interior of the cell, however, remains as a possible source of noise.

These examples bring out some of the difficulties encountered when the measurement under consideration is no longer in the large-scale range, where there is necessarily an averaging over the random fluctuations. Certain orders of magnitude point up these difficulties. A bacterial cell has a total of about 10^6 or 10^7 protein molecules, which are subdivided into many molecular species. These molecules are aggregated into more complex structures, of which the total number is much smaller. In the extreme case of the single gene, perhaps one molecule is directly involved.

Uncertainty

Any measurement, whether physical or biological, has a certain amount of uncertainty. Part of this uncertainty lies in the fact that all measurement is subject to experimental error, imperfectly controlled environment, and other factors which are beyond the experimenter's control. In addition, precise measurement of small-scale phenomena is limited by the Heisenberg uncertainty principle. Brillouin[5] has pointed to a further uncertainty of measurement, indicating that the minimum increase of entropy (in the object of measurement, instrument, and observer) accompanying a measurement must be k, Boltzmann's constant.

Biological measurements involve all the uncertainties pointed out in the previous paragraph, although they do not occur in a range where the Heisenberg uncertainty principle causes any difficulty. The most important difficulty involves the uncertainty due to the many uncontrolled factors which influence the measurement. In addition, living systems are open systems, far from equilibrium, in which irreversible processes are taking place. In such systems, it is difficult to predict the result of a perturbation such as those caused by the measuring process.

Significance for Instrumentation

> Therefore most of the exact sciences measure things—that is to say, they compare them with some standards and express the results as numbers.
>
> —J. Z. Young.

The chief factor which distinguishes biological instrumentation from conventional types of instrumentation is the design of the sensing probe. The other components of the instrument system, such as communication channel, amplifier, recorder, and observer are common problems shared by various fields of instrumentation. In addition, it should be realized that, for many problems of biological measurement, the instrumentation is adequate, but the preparation of the material requires critical insight if the measurement is to have significance.

The design of the probe requires certain general considerations:

(1) *Minimum perturbation.* Often a compromise must be made between sensitivity and precision on the one hand and probe size on the other.

(2) *Precision and variance.* The variance of the measured quantity should determine the necessary precision. It is uneconomical to strive for greater

precision in a single measurement than is justified by the variance of a set of measurements.

(3) *Signal sensitivity.* After a decision has been made as to what physical quantity the probe is to measure, it must be designed so that variations in other physical quantities have a minimum effect on the output. This is also true in nonbiological systems.

Approaching the subject from a more practical level, it would seem that the problem of biological instrumentation is a part of the larger problem of developing a discipline to give meaning to biological measurement. The responsibility of deciding which measurements to make (which sensing elements to use and how to make them interact with the systems to be measured) is therefore the biologist's problem. For it is only within the context of the theory of a given discipline that a particular set of operations can yield interpretable data. Measuring techniques must be evolved to fit each problem, and the biologist should not expect to buy his research instruments ready made any more than a physicist should so expect. The great advances in experimental physics have not come from men who have purchased a commercial instrument and taken measurements. They have rather come from men like Millikan, with his oil drop apparatus, or Michelson and Morley, with their optical equipment. The advances have come when men have designed a specific apparatus to provide an answer to a question framed by a background of theory. It would also seem that biologists must design apparatus consistent with a theoretical framework and that the subsequent measurements are interpretable or at least meaningful. To expect that unmodified commercial instruments will always serve in this way is a surrender of the biologist's claim to understanding his own field or, at least, an admission that the instrument manufacturer has a better understanding of biological problems than that possessed by the instrument user.

This assertion is not to deny that a great deal of very valuable research is performed with commercial equipment. It is rather to assert that a measurement is not an act in isolation, but must be connected with a discipline which gives meaning to the measurement. This connection is clearly the responsibility of those trying to develop the discipline and take the measurements.

What function does this leave the instrument engineer who wishes to contribute to biological instrumentation? I think that there are three possibilities for such an individual: First, he may become a biologist in the sense that he may learn enough biology to develop instruments and techniques which make sense for their biological applications. Second, he may act in a consulting capacity in advising the biologist what is available in terms of transducers, amplifiers, and the like. Third, he may devote himself to that part of the system which is common to all instrument systems and may aid in that part of a project.

The biologist, on the other hand, must acquaint himself sufficiently with optics, mechanics, electronics, and so forth, to be able to understand the design of his experiment. Here, I think that the education of biologists is subject to improvement. The inclusion of a university course for biologists on basic instrumentation, instrument design and use, and the theory of measurement should aid the biologist in developing new techniques to answer new questions.

Discussion

When a particular science encounters problems which for some reason or another cannot be solved by its own methods but which are nevertheless of an urgent nature, and which are perhaps of great importance to that particular science itself, then that special branch of science is induced to discover a philosophy which it can use and apply for its own purposes. It is obliged to deal with questions which for the most part we do not know how to express in the usual form and with the usual precision—inasmuch as they extend, in one direction, behind the normal assumptions of this particular science, and in the other, far beyond its results.

—Bruno Baron von Freytag gen Loringhoff.

The preceding analysis may have seemed discouraging to those who look to instrumentation to solve the many baffling mysteries of living systems. Rather than serving as a discouragement, an understanding of the difficulties should serve as a challenge to those who would attempt to understand biological phenomena in terms of quantitative data.

The problems of biological instrumentation go to the core of our understanding of biological processes. Judging which measurements are significant implies an understanding of the significant questions which a science may pose, and this understanding implies considerable maturity and theoretical foundation. Biological instrumentation cannot be separated from biological theory, for the meaning of each measurement must be sought in the instrument, the measuring process, and the nature of the material being measured.

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MEASUREMENT AS A HUMAN ACTIVITY

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Instrumentation is a broad, horizontal aspect of modern technology. As such, it reflects certain basic human characteristics, notably curiosity about the environment and the drive toward power by control over the environment. Full understanding of instrumentation therefore can be anticipated only if the field is viewed as being, among other things, an arena of human activity, human purpose, human fulfilment.

It is therefore my intention, in this paper, to try first to find in the ultimate "grass roots" of human consciousness some of the elements which appear to be basic in the process of measurement, and then to develop from this "humanistic" background some fresh insights into theoretical instrumentation.

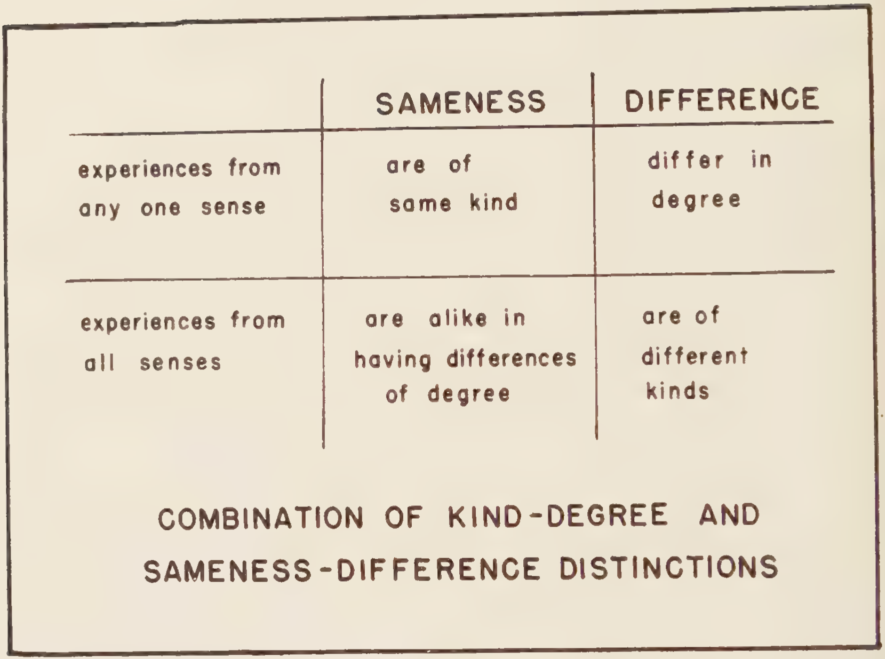
Now I know that any attempt to analyze human consciousness is a most difficult and complex undertaking.[1] With no pretense here of a formal treatment, even of those aspects relating to measurement, I limit myself to presentation of a few thoughts about the human mind which help me view measurement as a human activity.

Perhaps a good test as to whether a given concept is a truly basic element of consciousness is to ask whether it is ordinarily taken completely for granted. Certainly the first concept I wish to consider meets this criterion. For I call to attention our ability to be aware of sameness and of difference. This ability is the faculty we exercise whenever we make distinctions, including, unfortunately, the distinction between sameness and difference. The circularity in which we become entangled warns us that the concept of sameness is completely undefinable. Rather than seeking to define it, we may reverse our stand and use it to define mind. Accordingly, let us take as our starting point this statement: *Mind is that which can be aware of sameness and of difference.*

Given: such a mind, coupled to a variety of sense organs. It then seems reasonable to assume that the sense experiences from any one kind of sense organ would be apprehended in the mind as having a certain sameness, recognized ultimately as establishing the *kind* of the experience; and a certain difference, recognized ultimately as establishing the *degree* of the experience. Thus the distinction of kind and degree, of quality and quantity, arises naturally from the diversity of sensory equipment.

(The foregoing exposition is oversimplified in that the sense experiences, particularly visual and auditory, are multidimensional, and each dimension should be treated as establishing a kind of experience. However, it is plausible to assume, as a beginning, the unidimensional senses, with the later diversification to multidimensional being part of the same developmental process which includes extension of kind and degree to abstract thoughts and feelings.)

Sometimes the whole is greater than the sum of its parts. If the sameness-difference distinction is added to the kind-degree distinction, a crucial combination step follows. This is the recognition of a *sameness in the differences* of



	SAMENESS	DIFFERENCE
experiences from any one sense	are of same kind	differ in degree
experiences from all senses	are alike in having differences of degree	are of different kinds

COMBINATION OF KIND-DEGREE AND SAMENESS-DIFFERENCE DISTINCTIONS

FIGURE 1

the various kinds of experience. Thus, meaning becomes attached to degree, implying some sameness for all kinds of experience. The relationships are arrayed in FIGURE 1. It is clear that filling in the lower left-hand place—recognition of the general concept of degree—requires higher-order abstraction than the others, and so could be expected to occur later in the individual or race.

It is important to consider how the general concept of degree and the general concept of order are related. Since ordering may be in time or in space, as well as in degree, the general concept of order appears to be at a still higher level of abstraction. Particularly, the perception of temporal order seems to differ from that of degree; and the spatial order often called arrangement or pattern is also removed, though perhaps not so far, from order of degree. Thus, the general abstraction represented by the ordinal numbers seems to have several distinct representations (space, time, degree) in human consciousness.

Having come *via* the sameness-difference and kind-degree dualities to the ordinal numbers, one is presumably ready to use ordinal scales. The extension to metrical scales, though, of course, very important, is a more advanced step which need not be treated here.[2, 3]

But the whole concept developed above, of measurement as the relatively passive estimation of degree of experience, needs review and supplement. The general pattern of human interaction with the environment is shown in the simple block diagram of FIGURE 2. The individual observes and acts on the

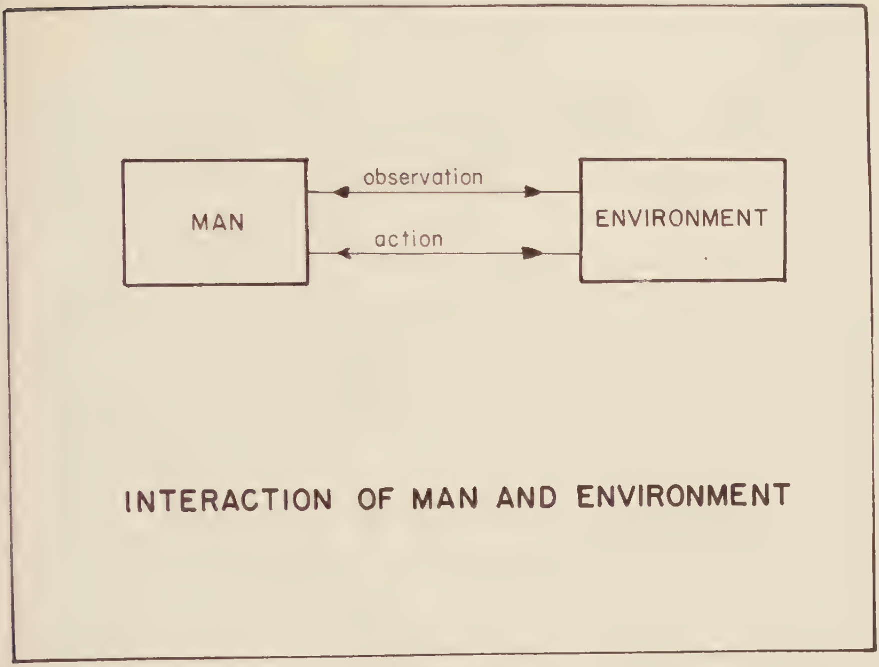


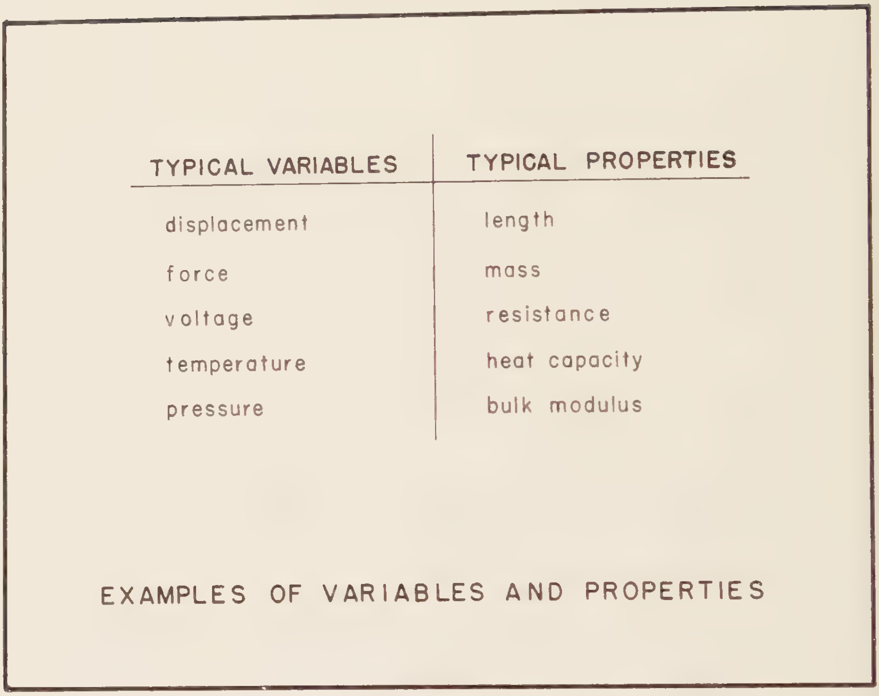
FIGURE 2

environment and is in turn observed and acted upon by the environment. But what is meant by the words "action" and "observation"? And what is symbolized by the lines and arrows of FIGURE 2?

According to the idea of measurement or observation growing out of the natural estimation of degree of sense experience, the individual's act of observing the environment corresponds to his being *subject* to the environment, his *receiving* from the environment the impression on his senses. This act suggests an arrow pointing toward the individual. On the other hand, making an observation may also imply initiative and, in this sense, is like action on the environment, portrayed by an arrow pointed toward the environment. In the act of observing, what goes to the environment, and what is received from the environment?

It is clear from ordinary human experience that some information comes to the individual without his asking for it, while other information can be had only by active questioning. If I sit on my porch, for example, and a bird flies by, the fact of the bird's motion would be evident to me without further initiative on my part. But if I wish to know the mass of the bird or the feel of his feathers, I must take action—not only to catch the bird but then, also, specifically to satisfy my curiosity.

Many more examples of observation and measurement could be cited to support the classification of all measured quantities into two groups, properties



TYPICAL VARIABLES	TYPICAL PROPERTIES
displacement	length
force	mass
voltage	resistance
temperature	heat capacity
pressure	bulk modulus

EXAMPLES OF VARIABLES AND PROPERTIES

FIGURE 3

and variables.* Variables are quantities which in some sense manifest themselves. Properties are quantities imputed to the environment[4] to help in understanding and remembering the variable-manifestations. Measurement of variables corresponds to the rather passive estimation of degree of experience to which one is subject. Measurement of properties corresponds to "testing" of the environment by exercising the prerogative of action.

Thus in FIGURE 2, arrows must point both ways for proper symbolization of measurement. The individual *interacts with* the environment in the measuring process. The nature and meaning of this interaction are partially revealed in the property-variable duality.

In FIGURE 3 are listed some examples of physical quantities, classified into variables and properties. Notice that the two quantities of the first example both have the same dimension, length.

In FIGURE 4 are listed some statements of comparison between properties and variables. Variables are quantities which change in time. Properties are relatively fixed. Accordingly, in the differential equations describing physical systems, the variables appear typically as the dependent quantities, while properties appear as coefficients, most often constant, but occasionally time-

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* I discussed certain aspects of the property-variable duality during April and May, 1954, in talks given to the Engineering Mechanics Seminar of Purdue University, to Instrument Society of America sections in Tulsa, Oklahoma, and Austin and Beaumont, Texas, and to an instrument and controls group at Oak Ridge National Laboratory, Oak Ridge, Tenn.

SYSTEM VARIABLES	SYSTEM PROPERTIES
time-dependent	generally constant
dependent variables in diff. equations	coefficients in diff. equations
interaction (lines)	systems (blocks)
measured by instrument receiving energy	measured by instrument supplying energy
forms of energy	means of manipulating energy

COMPARISON OF VARIABLES AND PROPERTIES

FIGURE 4

dependent and, most important, in control systems dependent on the controlled variable. In block diagrams, variables are portrayed by the lines of interaction, while properties pertain to the component systems symbolized by blocks. The last two items in FIGURE 4 will be given special discussion and will be formally stated as the "first law" and the "second law" of the property-variable duality.

The polarity of energy flow between instrument and system being measured was foreshadowed in the above discussion of FIGURE 2. But, specifically for physical measurements, there seems to be a fixed rule that, in measurement of variables, energy flows into the instrument, while, for measurement of properties, energy flows from the instrument. Perhaps the simplest example is measurement of voltage, where energy flows into the voltmeter and is stored in coil deflection and dissipated in resistance of coil winding, and measurement of electrical resistance, where current and hence energy must be made to flow into the resistor. The first law of the property-variable duality may be stated thus: *In measurement of variables, energy flows to the instrument; in measuring properties of passive systems, energy must be supplied by the instrument.*

The restriction to passive systems is necessary, because otherwise the simultaneous measurement of two or more variables will determine the value of properties. An example would be measurement of resistance by simultaneous measurement of current and voltage, for a resistor in a network in which currents already were flowing. Viewed in this light, a property such as resistance is something which is postulated, not experienced, by man. Admittedly, an entire science, such as astronomy, can be built on such indirect postulation of properties. But it is interesting to note the recent reflection of radio waves from the moon as the first direct measurement of a property of a celestial body; and, epistemologically, it seems to me, sciences or portions of sciences should be considered basically different according as direct measurement of properties is or is not possible. Not only the interpretation of remote and inaccessible space, but also all interpretation of the remote past, as in paleontology, is indirect science.

There is an important exception to the first law, involving temperature. Strictly speaking, there are no passive elements at any temperature above absolute zero. Again making use of electrical resistance as an example, we see that, by simultaneous measurement of temperature and of thermal "noise" voltage, the resistance may be measured without supplying current to the resistor.

Moreover, temperature may violate the first law with respect to measurement of variables. For in measuring temperature (a variable), energy in the form of heat may flow from or to the thermometer, according as it is initially hotter or colder than the object being measured. Evidently temperature, in the light of the property-variable duality, is a very special quantity.

The second law concerns manipulation of energy and may be stated thus: *Every amplifier involves a changing property.* Since every automatic control loop includes an amplifier, the second law implies that the typical constant-coefficient treatment of control systems must be in every case an approximation. Upon consideration, it is clear that switches, valves (including electronic valves or vacuum tubes), the animal organism, and any other "devices" capable of permitting (power) amplification, all embody a property which changes, continuously or discontinuously. In an automatic control system, this changing property is made to depend on the controlled variable and accordingly, as mentioned earlier, appears in the differential equation as a coefficient depending on the dependent variable. Hence, as a corollary to the second law we have: *Every feedback control system is nonlinear.* The linear approximation is, of course, always useful and often sufficient.

To summarize, we may say that measurement, viewed as a human activity, is in part the passive effort of the human mind to introduce order into the welter of sense impressions; and, in part, the active human effort to taste and test the structure imputed to the environment in explanation of the sense experience. We have amplified the classic instrumentation duality of measurement and control into a threefold progression, representing increasing degrees of human interference with the environment: first, measurement of variables, or apprehension of degrees of experience caused by self-manifesting reality; second, measurement of properties, or testing of postulated structural reality; and, third, control, or action, the deliberate changing of properties to suit human purpose.

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Part II. The Transmission of Instrument Requirements and Specifications

CONTRIBUTION OF THE ATOMIC AGE TO INSTRUMENTATION

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Introduction

The atomic bomb was developed as part of a war effort during which scientists were particularly frantic in their search for new instruments, new detector systems, and equipment of many types. The development did not stop with the war but, in fact, has continued at an active pace both in atomic fields and out of them. The purpose of this paper is to identify, if possible, the developments that can be traced to the introduction of the atomic age. In particular, it would be desirable to see whether we have gotten our money's worth in instrumentation from the atomic effort.

The early atomic effort largely made use of instrument techniques that were available in the university research laboratories or industrial plants, with a few notable exceptions. The difficult problems of the atomic effort were those of new chemistry, chemical analysis, metallurgy, physics, reactor calculations, and plant design. Even the radiochemical plants, where the intense radioactivity required shielding with three or more feet of concrete, were largely made to operate with a brute-force adaptation of conventional, available equipment.

The picture has changed for the better since the end of the war, although probably not nearly in proportion to the magnitude of money and effort that has been going into the atom. In general, the appreciation for the new specifications that are called for by the nuclear reactor, the radiochemical plant, and by research activities wherein radioactive materials are used, has been slow to develop.

Analytic Chemistry Techniques

The problems of analytic chemistry associated with metals such as uranium, thorium, zirconium, beryllium, are very great indeed. This assertion is true both because of the wide range of concentrations of impurities that are of interest, ranging from a few parts and up per hundred million, and also because so many dozens of atom types become involved in the form of ore contaminants, rare earths, and fission products. The chemistry complications are such as to demand a major effort to develop nonchemical tests for contaminant and concentration determination. Spectrochemical methods have been particularly interesting in cases where chemical methods have been most seriously handicapped, for example in the analysis of hafnium-zirconium mixtures over the entire concentration range, and for identifying trace impurities.

In recent years, spectrographic analysis has received a boost because there are available improved photographic emulsions that permit precision of as good as ±1 per cent in some cases. For the measurement of spectral line intensities, there are now available improved light-detecting devices which permit direct reading to avoid emulsion development and calibration problems. Time required for an analysis has become reduced from hours for chemical methods to minutes for photographic spectrometer methods, to less than one minute to perform analysis for 20 or more constituents, with precision of better than ±0.5 per cent, in the case of direct-reading spectrometers.

The photomultiplier tube has been made considerably more useful by improving both the tube itself and the associated circuitry to give greater stability and lower noise level. The fluorimeter, which can be so useful for measuring the low concentrations of uranium fluoride, has been improved with the use of photomultipliers to permit sensitivity to concentrations of 5×10^{-10} grams of uranium.

This same photomultiplier tube, coupled with a scintillator, has become a sensitive detector and discriminator of radiation. Many types of liquid and crystal scintillators have been studied in this connection, both for fundamental research purposes and for routine analysis for fission products.

It would be well to note certain analytic chemistry techniques that have become exceedingly useful in the atomic program for separating trace quantities of fission products and other atoms. For example, when nuclear reactions are produced by bombardment of heavy elements, it is necessary to separate the products to determine the nature of their radioactivity in order to understand better the mechanism of the nuclear reaction. The ion exchange resins have become very useful in this regard, permitting separation of trace elements. Similarly, chelating agents have received much attention for similar uses.

The solvent extraction technique has had long usage as an analytic tool. Under the impetus of the atom effort, it has been expanded in the variety of solvents and data that are available. The technique has been useful in production work and has found refinements in the form of countercurrent microrotary extractors useful for quite complete separation of milligram quantities of uranium in 10- to 15-centimeter columns.

Fluorimetric techniques sometimes fail because of the presence of elements that quench the fluorescence. Sometimes, also, one wishes to know the uranium content more accurately, and to lesser concentrations, than is permitted by the fluorimeter, in which case one can make use of a paper chromatographic technique developed in Britain. According to this method, uranium in aqueous solution containing free nitric acid is absorbed on partially nitrated cellulose packed in a glass column. The absorbed uranium is then selectively extracted from the column with diethyl ether containing nitric acid, and the uranium in the solvent is then determined fluorimetrically. Microgram quantities can be detected fairly easily by this method.

MASS SPECTROSCOPY

Mass spectroscopy has received detailed attention for many years. The diffusion plants were greatly helped by this instrument both for gas flow monitoring and for leak-testing of vessels. These instruments were based largely on the old principles by which ions having differing mass to charge ratios became separated in the course of electrostatic acceleration and magnetic deflection. Since the early 1940's, some work has been done to make analysis of solids easier than it had been, but this valuable instrument is still largely limited to the measurement of gases and volatile liquids almost in the form developed for use in the hydrocarbon industry. A great deal more work needs to be done to improve methods for introducing and ionizing solid specimens for analysis.

Meanwhile, a number of other interesting mass-sensitive devices have been introduced, using time-of-flight principles and high-frequency acceleration through multigrid structures. Some of these methods have been used successfully for studying rates of chemical reactions.

Research on microwave absorption in gases has been very fruitful for studying physical properties of gas molecules. As the frequency of the microwaves in a chamber is varied, say within a band in the frequency range from 18,000 to 27,000 megacycles/sec., it is found that a gas contained within the chamber will present a spectrum of energy absorption which is specific to the gas. It turns out that this absorption method can also be used to measure isotopic ratios, say for determination of nitrogen^{14} to nitrogen^{15} ratios in ammonia, or of carbon^{13} in cyanogen chloride with an error of less than 2 per cent in the range 1.1 per cent to 10 per cent C 13.

Analytic Techniques Using Nuclear Interaction

The atomic age has been characterized by the liberal production of nuclear particles in machines, the most important being neutrons in the nuclear reactor. Interaction of these particles with the atoms has been the subject for detailed measurement and study for some years, and the past two decades have seen the atomic chart blossom out into a very large collection of stable and unstable atoms. Each atom has its own mass, charge, and interaction behavior if it is stable, and of disintegration behavior if it is unstable. Frequently, it is easy to identify contaminant atoms with amazing sensitivity, to 10^{-10} gm., by bombarding the specimen to be analyzed and measuring the radiation emitted by the contaminant products. Neutrons are particularly effective in transmuting atoms, and the intense neutron fluxes of nuclear reactors make this activation method particularly useful.

For example, using reactor neutrons at Oak Ridge, iridium running only one part per billion can be detected in pure platinum, and manganese contamination as small as 0.6 ppm. can be detected in samples of ultra pure commercial hydrous aluminum oxide. The technique has become a routine tool in many laboratories, using either neutron bombardment or bombardment with charged particles.

Other methods make use of the differences among atoms in their absorption or scattering of nuclear particles. Particularly in the transmission of slow neutrons, it can be shown that many atoms show a spectral pattern that is specific to each isotope, and the phenomenon can be made use of to identify materials and the presence of impurities, nondestructively.

Atomic Age Contributions

How much has the atomic age added to instrumentation? We have listed the above contributions, and it is proper to assume that other contributions exist under security wraps.

To get a better measure of these contributions, one must recall that: (1) the atomic effort has required solving a long succession of difficult technical problems with the help of many of the world's leading scientists and engineers; (2) the problems of measurement have been exceedingly difficult and novel throughout this whole effort; and (3) well over ten billions of dollars have gone into this effort, and many tens of thousands of the country's best engineers have contributed to the work.

In view of the magnitude and quality of this effort, one develops a suspicion that we have been shortchanged as far as major atomic contribution to instrumentation is concerned. This suspicion appears all the more tenable if one were to press the point that most of the contributions described herein were not born of the atomic effort, but were simply adopted and expanded in application.

Assuming this inference to be true for the moment, what may account for the disproportion? At least several factors may be mentioned.

We have already observed that when the atomic plants were first set up, there was not time to look for nice instrument solutions to the measurement and process control or reactor control problems. Known instrument techniques were accordingly adopted, or engineered by brute-force methods, to do the job at hand. Needless to say, the plants operated, but in a manner that was prodigal in money and manpower, and short on efficiency and basic innovations.

At the close of World War II, there was little respite, for atomic defense needs again came to the forefront and, once again, urgent plant construction programs prevented introduction of nice solutions to these problems. We are still essentially in this situation of stress.

Security curtains have encouraged inbreeding of ideas among the cleared staff and, in the absence of true competition among the instrument specialists, this inbreeding has tended to maintain the *status quo* with only moderate disturbance to existing operations.

One might ask where the instrument companies have been all this time, as well as the many researchers whose business is instrumentation and measurement. The instrument people were indeed in the thick of it, but urgent delivery schedules did not permit them to do more than simply supply on demand. Too often, they supplied material without having the slightest idea what the application would be.

Due partly to the security curtain, partly to the newness of the whole business and to its complexity, partly to inertia and preoccupation with the profits of the day, and partly to the difficulty of developing clear concepts as to the new trends and specifications on instrumentation, the instrument companies have failed to respond in a positive manner even to the present time.

The answer to this problem would appear to lie in a direction that calls for fewer security obstacles, more interest on the part of instrument people in learning the special requirements of this new technology, more opportunity afforded them to develop their own concepts of the required specifications, and more emphasis on competitive thinking on technical problems.

The need for a drastically new approach is indicated both with respect to the instrument problems of the nuclear reactor and radiochemical processing plant, and with respect to laboratory operations involving radioactive materials. In the first category, one must measure and control process variables and solutions in areas where the intense radioactivity requires operating behind many feet of concrete shielding. The devices that are normally used for measurement of pressure, flow rate, liquid level, radiation, process liquid composition, and devices for pumping, sampling, and analyzing, become woefully inadequate under these conditions. Replacement of equipment must be done by remote manipulation, and this procedure sets a particular premium on equipment that assures long life and that can be replaced without disassembling the system by remote manipulation. Wholly new instrument concepts need to be developed to guide the industry.

Similarly, the problems continue into the analytic laboratory where radioactivity is introduced. Although the tolerance quantities for ingestion are particularly small, and, therefore, the analytical chemist must avoid breathing and handling the solutions, the laboratory apparatus given him scarcely permits the assurance and protection he should have. His most frequent operations, namely weighing and volume determination, still must be accomplished by close visual observation and by hand or awkward tongs, under hoods that sometimes increase this hazard because of the air suction. This awkwardness exists to varying degrees with almost every other measurement he attempts, whether it involves density, pressure, surface tension, ion content, X-ray diffraction, or any one of many other measurements.

To the writer, these problems mean that instrument development accomplishments to date have not been commensurate with the money and technical effort spent on the atom, and that a more critical evaluation of present efforts is required.

INSTRUMENT REQUIREMENTS AND SPECIFICATIONS IN BIOELECTRIC RECORDING

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The uses of bioelectric recording may be classified according to the type of information sought by this means: (1) Studies on the nature of the bioelectric activity itself sometimes involve specialized and often elaborate instrumentation. (2) Use of the bioelectric responses as a means of information regarding the communication and effector networks, in which the bioelectric activity itself plays a major role, is perhaps the largest branch of electrophysiological research. (3) Use, as an index, of the behavior of important organs or systems of the body has become widespread because of its importance in clinical medicine. This class of applications has grown into a number of separate branches such as electrocardiography, electromyography, and others. Relative newcomers are electrogastrography, the measurement of potentials produced by the secretory activity of the stomach, and the use of bioelectric activity in a servo system to monitor and control administration of anesthesia. Each of these branches has a central core of research activity and a much wider sphere as a tool in medical practice.

Since present-day uses of bioelectric recording encompass so wide a range of problems, it will be necessary to confine this discussion to those aspects of instrument requirements and specifications which might meet the needs of the majority of workers in the field. The most advanced, pioneering problems, which often call for highly original and exciting applications of instrumentation engineering, therefore, cannot be considered except in a few references.

The requirements for instrumentation in bioelectric recording are determined by the specific characteristics of the electrogenic units.* These requirements may differ widely in their nature, structure, properties, and actions. For example, some unit bioelectric generators in the nervous system are more or less spherical cells or neurons of the order of 10 to 30 μ in diameter. In rare cases they are easily accessible to manipulation but, in most instances, are buried in a mass of similar or other types of tissue. The latter may itself be bioelectrically active or inert. Other cells have more or less spherical bodies and very extensive filamentous branching extending for distances 100 or more times farther than the diameter. These branches or dendrites may be distributed with various degrees of asymmetry in the volume around the cell body. The nerve fiber or axon of the cell is a cylinder, in most cases not more than 20 μ in diameter but, in some, nearly 1 mm. The fiber may be shorter than 1 mm. or extend, as in mammals, from the tips of the toes to the base of the skull. Many fibers have relatively thick, surrounding, highly insulating sheaths, interrupted at more or less regular intervals, like a wire covered with a string of elongated glass beads. Some of the bioelectric cells exhibit other types of activity more striking than the electrical. For example, muscle fibers develop a mechanical response which is longer-lasting than the bioelectric and is easily seen; glands cause secretions. Nervous tissue, which is specialized for communications purposes, exhibits much more subtle chemical and physical changes which are an accompaniment of their electrical activity.

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* A good elementary introduction to electrophysiology is the book by Brazier[1] Dickinson's[2] and Whitfield's[3] books discuss techniques and particularly the electronic elements.

The medium surrounding individual cells is essentially a salt solution of rather elaborate composition, and the interior of the cell is composed of still more complicated and structurally complex substances, collectively known as protoplasm. The solid material of the protoplasm is, however, relatively sparse and constitutes, by dry weight, perhaps 5 to 10 per cent of the cell. The rest is made up of water in which are dissolved various salts, but in different concentrations from those in the surrounding fluids. The resistances of the exterior and interior are probably nearly identical, but the separating boundary or membrane, though submicroscopic in thickness, has high resistance and capacity. The membrane is the seat of the electromotive generator which acts through what appear to be very complex, as yet imperfectly understood electrochemical mechanisms. The resistance of this submicroscopic membrane is of the order of 1000 ohm-cm.^{2}, while the capacity varies over a wide range. In various nerve and muscle fibers, the capacity attains values of 1.0 to about 20 μF cm.$^{-2}$. This, presumably, is due to the thin filmlike structure of the membrane, which is supposed to be constructed of a few layers of protein and lipoid molecules. This membrane would have very high specific resistance (of the order of 10^9 ohm-cm.). The dielectric constant might be about five and perhaps much more. The fluid on either side of the membrane, with a specific resistance of only about 20 to 100 ohm-cm., forms the plates of the condenser.

At rest, the interior of the cell is usually negative to the exterior by approximately 50 to 100 mv., the precise value depending on the particular tissue or cell and on its conditions (FIGURE 1A). This resting potential therefore appears across a polarized membrane, and depends on the integrity, both anatomical and physiological, of the latter. The membrane can be excited by chemicals and by mechanical or electrical stimulation, and alters its properties for a brief time to produce a short pulse which has a time course characteristic of the cell and its operating conditions. In most of the cells of the body, this pulse is propagated away from the site of initiation by a characteristic process. In the equivalent circuit of the cell (FIGURES 1B, 1C), the network has the properties of a cable conductor. An electrical pulse impressed at one end is established everywhere in the cable at the speed of light, but its form and amplitude along the cable has a time course determined by the circuit properties of the cable. At a distant site, a short, large square pulse would be attenuated and deformed to a small, slowly rising, and decaying change. The same thing, of course, happens in the bioelectric tissue and, as in a transmission line, this behavior operates to degenerate the useful transmission of information. Engineering practice has solved this difficulty by periodically inserting loss-compensating devices, or amplifiers, into the line. The living cell devised a different mechanism, which operates as a continuously distributed amplifier. An impulse initiated at any place changes the membrane potential at this region (FIGURE 1). This causes a current flow through as-yet-inactive adjacent regions, which are then triggered to reproduce the same impulse locally. The impulse therefore travels without attenuation but, of course, at a price. The physicochemical reactions which are involved in the response at a given locus develop with a time course of action. The result is that the activity consists of an impulse of constant amplitude, but travelling with relatively low speed.

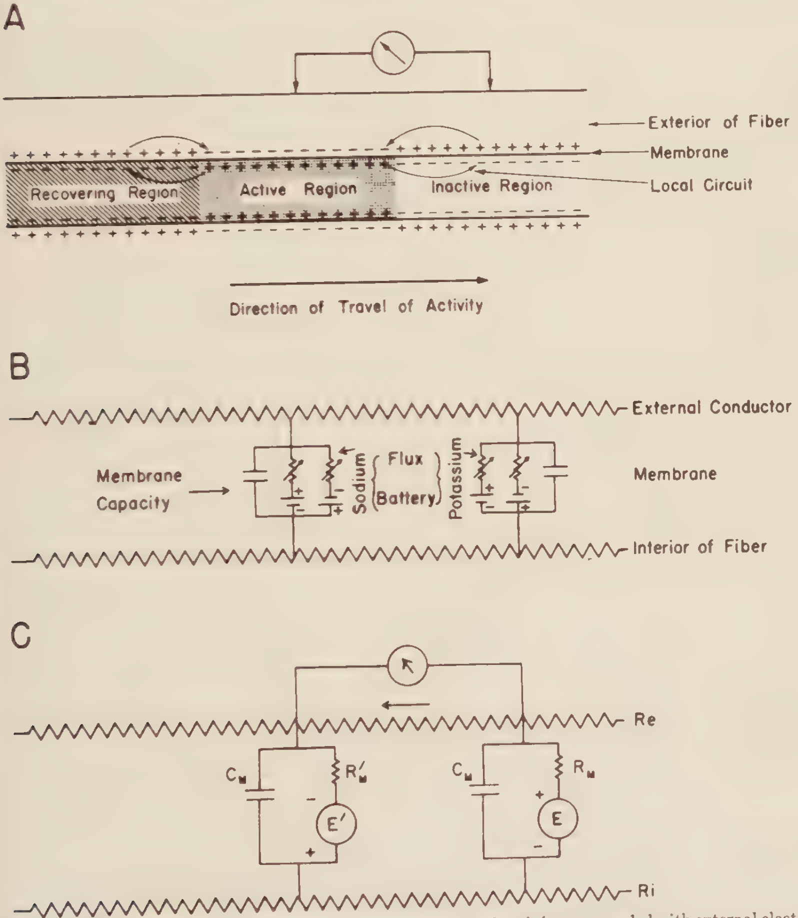

FIGURE 1. Diagrammatic representation of propagated electrical activity as recorded with external electrodes. (A) The change in potential as recorded with external electrodes is caused by a reversal of the membrane p.d. in the active region. A "local circuit" is established with current flowing outward through the membrane in an adjacent inactive region. If this current reaches sufficient intensity, that membrane is also excited into activity. Progressive repetition of this effect causes the impulse to travel along the fiber. The recorded response assumes a diphasic character (seen in FIGURE 5) as activity appears first under the one electrode and then under the other. (B) Electrochemical events during activity involve an increased *inward* sodium flux and, slightly later, an increased *outward* potassium flux. These fluxes are shown as variable resistances. Initially this movement places a sodium "battery" across the membrane of reversed sign to the resting potential difference. The later action of the potassium "battery" restores the initial charge on the membrane capacity. (C) The equivalent circuit of the cell during the response. The active region is represented by a generator (E′) of reversed potential relative to the inactive (E). The high membrane resistance at rest (R_M) is decreased to only a few per cent during activity (R'_M). The membrane capacity is unchanged. External recording electrodes record the IR drop caused by current flow across R_e, the exterior of the fiber.

The conduction velocity varies from about 150 meters per second down to extremely low velocities of a few mm. per second or less. The mechanism which causes the impulse is still only very partially understood, but it is clearly connected with the fact that the resting cell membrane is electrically polarized and that the distribution of ions inside the cell is different from the surrounding fluid. The impulse is probably caused by a very rapid switching in the characteristics of the membrane (FIGURE 1B). In many tissues, this switching permits a momentary inflow of sodium ions from the outside, where the concentration is as much as 10 times higher than inside, and a somewhat later outflow of potassium which is at a concentration about 30 times higher inside than out. These oppositely directed ionic currents, acting on the capacity of the membrane, cause the change of the electrochemical potential and its subsidence back to the original resting level.

The impulse itself is brief, lasting from about 0.5 to some milliseconds, and sometimes much longer, and has a characteristic form for the various tissues (FIGURE 2). The maximum potential of the cell, of course, is obtained when the recording electrodes are directly across the generator, with a minimum of shunting of the latter. This can be closely approximated by inserting one electrode into the cell and recording the potentials across the membrane. This measurement can be made readily with a large cell, such as the giant axon of squid, which is about 0.5 mm. in diameter, but requires special techniques when the cell is small. The problems of intracellular recording will be discussed later. While the amplitude of the resting potential is in the range of 50 to 100 mv., the impulse, or spike, is in the range of 100 to 150 mv. in many cells, and therefore represents a return toward the baseline of zero p.d. (depolarization) and a reversal of membrane potential (overshoot). The gradient of voltage rise is approximately 500 v./sec., the peak coming at about one third of the spike duration.

The bioelectric potentials can also be recorded with electrodes outside the cell. In that case, the measurement is of the IR drop across the external, shunting resistance (FIGURE 1) produced by the flow of the current generated by the cell. Inspection of FIGURE 1C makes it clear that the response of a group of cells can never be larger than the membrane potential of an individual generator, since all the cells are arranged in parallel. Only the electric fishes are capable of producing a voltage higher than that of the individual cells. This voltage is attained by a special adaptation, in which the cells of the electric organs have only one region of the membrane active, and are arranged in series-parallel (FIGURE 3). This arrangement permits summation of voltages and currents, and some electric fish may generate pulses of several hundred volts at one ampere or more.

Low Input Impedance Range

The simplest conditions of bioelectric recording are those with external electrodes placed on excised tissue. However, the instrumentation problems involved merge with those faced when the recording is made from the intact animal and the two cases may therefore be discussed together. They are characterized by relatively low interelectrode resistance. The considerations will be based on the use of a cathode-ray oscillograph for observation and/or recording, since other devices, such as ink writers, fall into a category of specialized applications for a limited range of phenomena, although widely employed in the study of these.

Amplifier sensitivity. The largest potentials which may be expected (except as noted before, in electric organs) fall in the range of 100 mv. but, because of

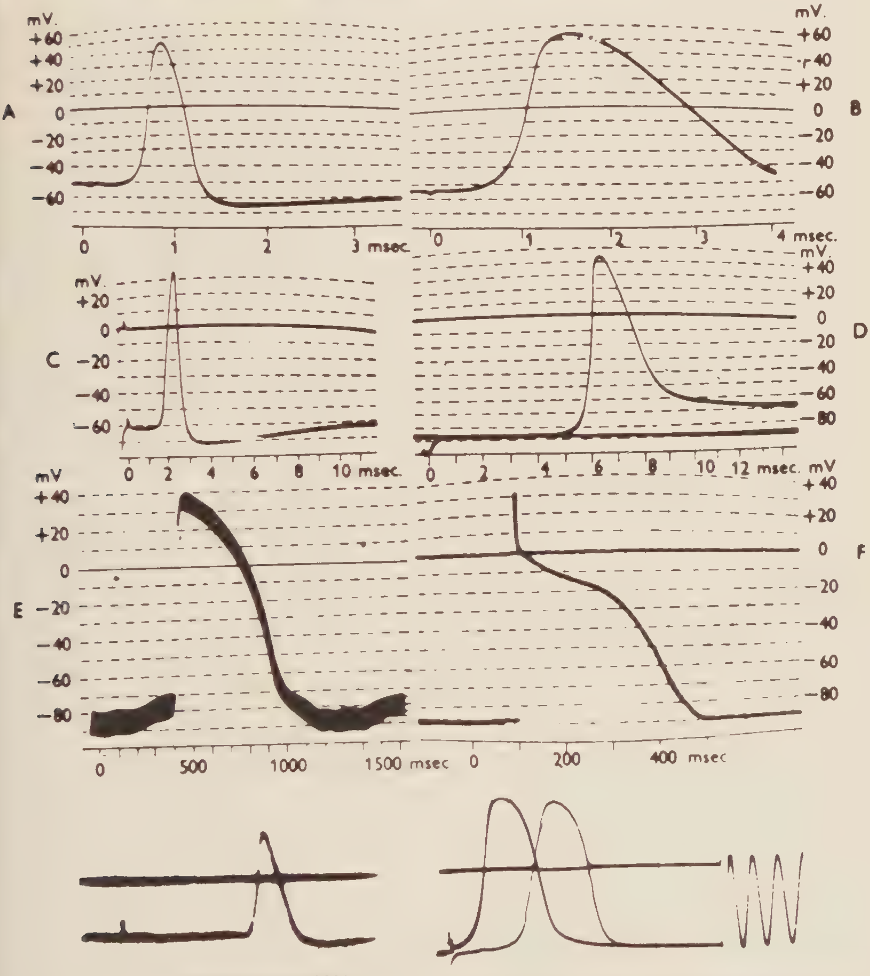

FIGURE 2. Samples of spikes generated in various excitable cells and recorded with intracellular electrodes. In each case, the resting level of p.d. across the membrane is interior negative. An overshoot representing reversed membrane p.d. develops during the spike. (A, B) Giant axon of the squid *Loligo* at 18.5° C. and 5° C. (C) Giant axon of another cephalopod, *Sepia* (D) Frog muscle fiber. (E, F) Fibers from frog and dog cardiac tissue. Below these on the *left*, the response of a tissue cultured chick spinal ganglion cell (resting potential about 44 mv. and spike 75 mv.). Time in msec. *Right:* Propagated response of the electroplaque of electric eel simultaneously recorded at two loci in the cell. Time and amplitude calibration, 1000 c.p.s. and 100 mv. (From H. Grundfest. The nature of the electrochemical potentials of bioelectric tissues.[20])

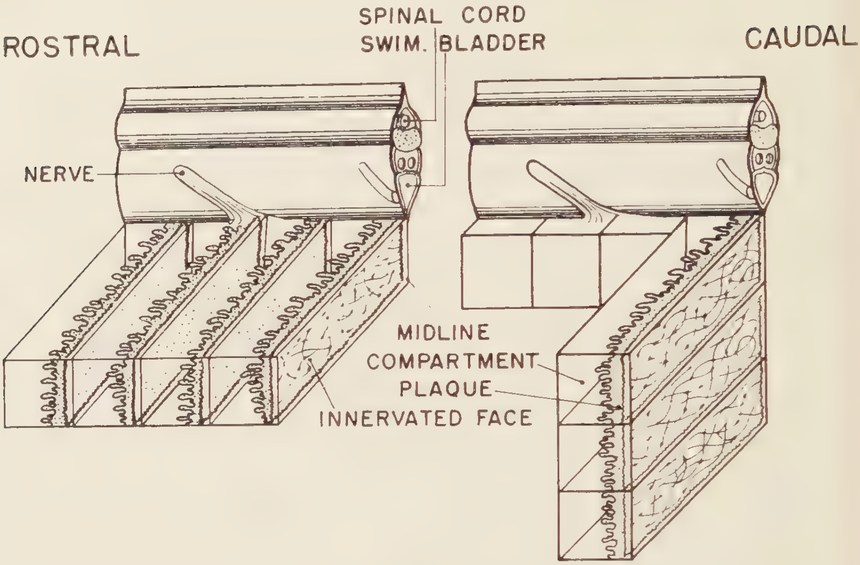

FIGURE 3. Series (left) and parallel (right) arrangements of cells in the electric organ of the electric eel. Each cell (plaque) occupies only part of a compartment. Only the caudal, innervated face of the cell has the specialized excitable membrane, while the highly digitated rostral face does not. Responses from a single cell such as are shown in FIGURE 2 are obtained only when the recording electrodes are across the caudal membrane.[21]

the losses suffered by shunting, the potential rarely exceeds and seldom attains 30 to 50 mv. even when recording from a nerve mounted in air. Oscillographs with maximum sensitivities up to 10 to 100 mv. per inch are commercially available and, in some cases, the most sensitive of these devices may be used directly connected to the tissue. In most applications, however, even with the excised nerve, and particularly when recording from intact tissue, the potentials obtained are much too small for the low sensitivity of the oscillograph. This phenomenon is due to several factors. Suppose (FIGURE 1C) that the external resistance (R_e) shunting the electrodes on a nerve is about 100 K ohms, while the sum of the longitudinal resistance of a nerve fiber (R_i) and the transverse resistance of the membrane (R_M) is 100 megohms. The potential recorded will be only 100 μv., although the generator itself develops 100 mv. The current developed during the activity would be about 10^{-9} A, and this much current has also been obtained experimentally.[18] These requirements are the approximate conditions for a 20 μ fiber in a nerve. Experimentally, it has been found that the potential recorded in this way varies directly with the diameter of the fiber. Therefore a response in a 1 μ fiber might be recorded as a potential of about 5 μv. When a group of fibers respond simultaneously, the summated IR drop across R_e of the currents produced by the parallel generators results in a proportionally larger signal at the electrodes, and 1000 of the largest fibers, responding synchronously, would be required to cause a 100 mv. spike. However, it is seldom that, in recording from intact tissue, the potential is as large as 1 mv., and it is very frequently only a few

μv. in amplitude. These specifications therefore set the range of sensitivities for the amplifier system: the amplifier should be capable of flexible adjustment of gain to handle and detect signals from about 100 mv. to several μv. in amplitude.

Precisely calibrated gain settings, long-term gain stability, and the independence of this gain stability from tube parameters are desirable features. They are not essential, however, if serious design complications are thereby introduced, or if their cost is high. This assertion is valid because, in most of the applications discussed here, the measurements are relative, since the amplitude of the recorded activity will vary with experimental conditions.

The location of gain controls should be carefully designed, for this feature will not only help to insure a wide range of sensitivities but can also be useful in diagnosing quickly many equipment breakdowns. Most amplifiers, particularly those in the packaged oscillographs, have a combination of coarse gain steps and an overlapping, continuously variable control. On the other hand, use of a fine step-gain control can relegate the continuously variable one to an auxiliary position. This control permits the investigator to shift from one sensitivity to another and back without the need to read dial settings accurately or to calibrate each time. In several laboratory-designed and laboratory-built units with which the writer worked for many years,* continuously variable controls for the X and Y deflection amplifiers were available but almost never used. Reading of fixed-position settings simplified considerably the recording of experiment protocols.

Amplifier noise. The requirements for signal to noise ratio cannot be specific precisely because the variability of the response is higher when only several fibers are active in an excised nerve, or when the activity derives from a complex structure such as a region of the central nervous system. In these cases, the potentials may be only a few μv. and the range of variability high. Therefore, it is desirable to have as low a noise level as possible. For the conditions described, the noise level generated within the amplifier and determined, of course, by the frequency band, can be brought close to the theoretical minimum.

Input impedance. The applications under discussion here are characterized, in general, by low interelectrode resistance, this resistance being of the order of 10 K to 500 K ohms. Therefore, the input resistance of the amplifiers might be satisfactory at 2 to 10 megohms. The input capacity in practical amplifiers is usually sufficiently low to satisfy the frequency requirements given below, and often the capacity of the recording electrodes and leads is the limiting factor as regards the latter.

Frequency range. The bioelectric activity has components which are equivalent to pulses of short duration (spike) and more sustained components (after potentials, *etc.*) lasting sometimes for seconds and, in some cases, on the order of minutes (FIGURE 4). Since the rising phase of the spike may be as brief as 0.1 msec., the *high-frequency* response of the amplifier system should be adequate for it. In practice, a 3 db loss at 50 to 100 kc. is fairly easy to achieve. The *low-frequency* range of the amplifier is more difficult to specify. Ideally, this should be for D.C. potentials and, in many applications, D.C. amplifiers are obligatory. Drifts and problems of balance then become important. Practical amplifiers have been described in which the drift is equivalent to a change of 10 to 50 μv./min. at the input.[4, 5] Whether drift can be reduced further depends on the contributions of electronic engineers and tube designers. Balancing of the amplifiers is partly a problem of drift, but it is also partly caused by the electrode system. Contact potentials between the electrodes and the tissue may be very large and may require compensation. This requirement means that balance controls must be easy to manipulate over a wide range of amplifier sensitivity, and that some means of setting the several stages of the amplifier at the proper operating value need to be provided. This may take the form of one or more meters permanently or temporarily switched in at strategic points, as well as appropriate controls. Variations in the contact potentials between electrodes and tissues are not strictly a problem for the amplifier designer, but such a designer must be prepared to defend his design against blame by the unwary or inexperienced user.

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* Some of these units were designed by the author in 1933 and others by Doctor J. F. Toennies in 1935. FIGURES 4, 7, and 8 are from records made 15 to 20 years ago.

In most applications, however, an RC-coupled amplifier is adequate and preferable. The time constant should be rather large. One second, which is a fairly common figure at present, permits measurement of many of the slower

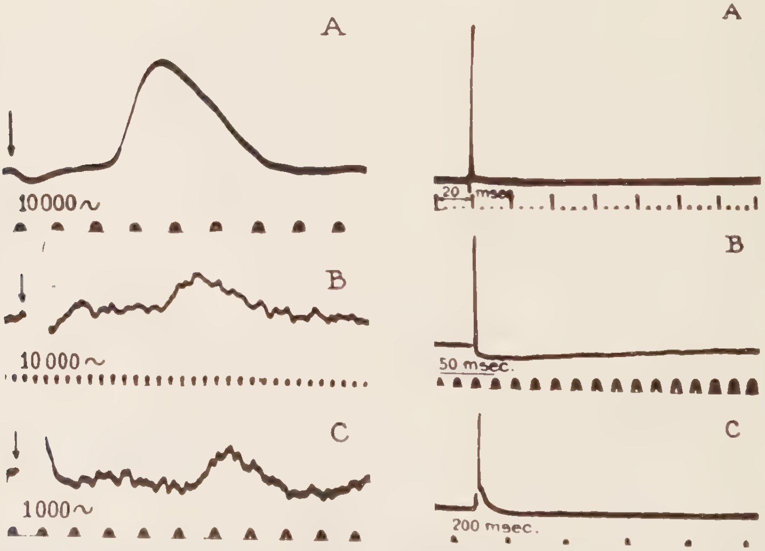

Figure 4. Responses of the A, B, and C groups of mammalian nerve fibers. *Left:* Spikes recorded from single axons of the three groups. The A spike is about 100 μv. in amplitude, the others about 10 μv. Note the tenfold difference in time scales. *Right:* The summated action potentials of a large number of fibers of the respective groups. In each record, the spike is the sharp peak and is followed by after-potentials. The type and time sequence of the action potential is characteristic for each group. The A fibers develop small negative and positive after-potentials following the spike. In the response of the B fibers the negative after-potential is absent, the spike being succeeded by a relatively large, longer-lasting positive after-potential. In the C fibers, both negative and positive after potentials are seen, but are larger relative to the spike and longer-lasting than in A fibers. Note the approximately 15-fold difference in the time scale.[22]

potentials that are encountered. On the other hand, a long time constant is often undesirable, as when the potential of the recording electrodes is shifting rapidly due to respiratory or other movements of the animal, while the activity being studied is a short-term event. The solution usually adopted to eliminate the large, slow, unwanted deflections in the base line is to decrease the time constant of the amplifier by decreasing the RC value of the coupling. Most amplifiers are provided with a range of values of time constants to give a choice of the low-frequency cutoff.

Another problem often encountered is the blocking time of the amplifier. Sometimes, the experimental conditions require high-amplifier sensitivity and the application to the tissues of large stimulating voltages. The latter, or other high amplitude signals, temporarily overload the amplifier, and recovery is not only slow, depending on the operating time constants but, when several RC couplings are used, it introduces damped baseline oscillations.[6] For these reasons, a minimum number of RC couplings is advisable, and a single such coupling is usually possible. Provision must then be made to check that the stages ahead, which are directly coupled and therefore subject to drift, are maintained at operating conditions.

Differential input. The input characteristics for general use have already been specified, but another desirable feature remains to be discussed. The relatively low signals to be recorded may often suffer interference from extraneous fields, such as line A.C. or high-frequency transients, including the stimulus artifact itself. In recording from a more or less intact animal, other electrical activity, such as the cardiac potentials or the potentials of contracting muscles, may interfere. Variations in the contact of the recording electrode caused by movements of the body may become troublesome. Finally, in attempting to record activity localized to the regions of the active electrode or, in attempting to record from several loci at once, cross-coupling due to activity elsewhere causes difficulties. This cross-coupling takes place in the IR drop of the common ground return. These difficulties may be minimized, and often eliminated, by differential recording in which the amplifier detects the difference between the potential to be recorded by an active electrode and the potential at an "indifferent" electrode. Extraneous interference or generalized activity of the animal is then picked up by both electrodes in common mode and rejected to the extent of the differential ratio of the amplifier. Common ground cross-coupling is also rejected in the same way. The differential ratio is often of the order of 5000:1, that is, a common mode signal 5000 units in amplitude gives a deflection as large as that produced by 1 unit out of phase. Differential amplifiers with ratios as high as 100,000:1 have been used. One design specification for a differential amplifier is the frequency characteristics of the differential formation. Many differential circuits perform with a high ratio at some specific frequency which decreases at higher or lower frequencies. Others have been designed with very high and flat differential formation over a range from D.C. to about 20 kc. Another insufficiently considered specification is the dynamic range of differential formation. Poor dynamic range means that the differential ratio may be high for a low inphase signal but will rapidly diminish as the applied inphase signal is increased. High inphase rejection for voltages up to 1 v. is desirable, and some amplifiers have been designed for a 20 v. common mode signal. These requirements seem to be extreme, but are not. If experiments at high sensitivity are carried out in open laboratories, not in shielded rooms, the interference picked up from wall and ceiling conduits is often several volts in amplitude. Finally, the stability of differential formation should be good, but design specifications cannot be given. Failing these specifications, ease of setting is important. In one type of A.C. amplifiers used in our laboratory,[4] the adjustment is made on a front panel-mounted potentiometer and a small, also panel-mounted trimming capacitor. In setting differential formation of a D.C. amplifier, independence of this adjustment from D.C. level changes in the circuit, or ease in checking and adjusting the latter are necessary. With a well-designed differential amplifier, it is usually possible to carry on experiments even with recording from intact animals, in an unshielded room with A.C. heaters, lights, and other equipment close to the recording site. The problem of dynamic range of differential formation is simplified, of course, by shielding carefully all A.C. power leads and terminations.

Since the amplifier is a bulky unit, often rack-mounted, leads from the tissue usually must be relatively long and may themselves pick up interference. Shielding, of course, adds to the capacity of the input and has two bad effects: (1) loss of high frequency response, and (2) loss of differential action by capacitative currents in the grid leads. For critical work, therefore, it is desirable to minimize these effects. This objective can be achieved by placing the input stage close to the tissue as a "probe" and coupling it to the rest of the amplifier through a low-impedance circuit. Input probes become even more important in applications to be described later.

Battery or power-line operation of equipment might be a major design consideration. Well-regulated high-voltage supplies are relatively easy to construct, although the ease may sometimes be deceptive.* For example, most highly regulated supplies are so regulated only for low-frequency conditions, whereas the amplifier they supply may have a wide-frequency band. In supplies for D.C. amplifiers, regulation must be not only against transient changes but also for absolute stability. Thus, changes in the reference level from day to day may alter voltages at operating points critically, although short-time drifts are satisfactorily eliminated. One advantage of power supplies is that they may be designed to have lower temperature dependence than batteries. When properly designed, they also may have much lower output impedance and therefore may be used to supply several amplifier units. Well-regulated low-voltage high-current supplies for heaters are apparently still troublesome. Several such supplies we have tried developed high magnetic fields which made them inconvenient for use in rack mounting together with the amplifier. One relatively simple solution is to use storage batteries floating across rather poorly regulated rectified sources, which are adjusted to supply, nearly exactly, the current drained by the heaters. Another procedure is to insert the heaters, in series, into the regulated high-voltage supply. However, unless special care is taken to avoid it, servicing the amplifiers for a burned-out tube becomes annoying, as does the difficulty in isolating one stage from another for the purpose of checking the equipment.

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* Doctor J. F. Toennies raised an important point in this connection in discussion of my paper before the 2nd A.I.E.E.-I.R.E. Conference on Electronic Instrumentation in Nucleonics and Medicine, Oct. 31, 1949.[7]

Most differential amplifier designs, excluding those using the Toennies differential circuit,[4, 8] carry the input symmetry throughout, and the output is then push-pull, against ground.[9] This symmetrical design has the advantage that, in so far as symmetry is achieved, variations in power supply or heater voltages are balanced out and, therefore, drifts may be minimized. Except in special designs, steady voltage of the output should be at or close to ground. Most commercially available oscillographs, however, cannot utilize fully the advantages of the symmetrical amplifiers. Whereas the majority of oscillographs now feature symmetrical input, it is possible to use them in this way only in the range of highest sensitivity, since the range switch itself is usually inserted into one side of the otherwise symmetrical oscillograph amplifier.

High Input Impedance Range

The second class of application of bioelectric recording which will be discussed here concerns intracellular potentials. As noted in connection with FIGURES 1 and 2, the interior of the resting cell is negative relative to the exterior (resting potential), and the response of activity (spike) represents a variation of the membrane potential in the positive direction, usually with an overshoot which causes the spike to reach amplitudes in the range of 100 mv. The maximum of these potentials is attained when the electrodes record directly at the generator, that is, across the membrane, and this maximum requires that one of the electrodes be inserted into the cell. Even in large cells, such as the giant axon of squid, however, this maneuver must be performed carefully. The generator, or membrane, is a living structure, and damage may cause distortion or loss of the potentials. Furthermore, the value of intracellular or transmembrane recording derives from the ability to study the steady resting potential, as well as the transient spike and whatever later changes in potential may occur. For this purpose, it is necessary to employ noise-free and electrochemically appropriate electrodes, which do not introduce substances injurious to the cell nor produce mechanical damage during penetration of the membrane. For these various reasons, as well as because of the relative ease in making them, fine glass pipettes, filled with a saline mixture or with 3M KCl are rather generally employed, although special metallic electrodes are also useful.

The micropipettes are made by pulling freehand or with machines, and have tapering tips which terminate in openings from 0.1 to several micra diameter, surrounded by thin glass walls. The mechanical problems of insertion are considerable, but are not germane to the present discussion. Two factors about the micropipettes, however, are important to the design of electronic instrumentation. The small bore of the opening means that the resistance of the electrode may reach values close to 100 megohms and will seldom fall below several megohms. The capacity across the wall of the capillary, between the inside fluid and the outer, then becomes important. This capacity has a magnitude of approximately 0.5 to 2 p.f. per mm. of the immersed capillary, when the ratio of the outer to inner wall diameter varies from about 2 to 1. The resistance and capacity are distributed. However, a simplified equivalent circuit is of a high series resistance terminated in a capacity to ground. The RC product becomes extremely high with fine electrode tips and results in very poor high-frequency response. Since the spike is usually a pulse with high-frequency components, distortions in amplitude and form are easily caused.

Solutions of this problem have taken two forms. In both, of course, stray capacity is minimized by placing the input amplifier stage as close to the electrode as is physically possible. In one method,[10] the electrode is as far as possible isolated from ground capacity, and a shield surrounding its major portion is carried to the cathode of a cathode follower which forms the input of the amplifier. As the grid moves with the potential of the impulse, the cathode and shield follow, the capacity between the latter and the electrode tip being thereby reduced.* A more complete correction of the high time constant is achieved by using a negative capacity amplifier.[11, 12, 13] The principle is to supply capacitative feedback to the input grid in such a way as to produce negative capacity which balances out the grid to ground capacity of the input. The amplifiers used in our laboratory have both this feature and cathode-coupling of the shield.† Negative capacity amplifiers may be made with a time constant as low as 20 to 40 μsec. for an input resistance of 100 megohms.

Grid current of the input tube becomes important in intracellular recording. Although precise data are scarce, it appears likely that most bioelectric tissues are stimulated by currents of 10^{-5} to 10^{-6} A/cm.^{2} flowing through the membrane for durations between 0.1 and 1.0 msec. If an electrode is inserted into the center of a spherical cell 20 μ in diameter, the membrane area subtended is about 10^{-5} cm.^{2} and grid current of 10^{-10} to 10^{-11} A may then stimulate the cell. Since it is desirable to affect the generator as little as possible, the grid current should be about 1 per cent of that value, or 10^{-12} to 10^{-13} A. Such low values are at present possible only by using special tube types and considerable selection. Most cells studied thus far with intracellular electrodes are somewhat larger and, since the area increases as the square of the diameter, grid current conditions then are less stringent. However, the need for amplifiers with extremely low grid current has already arisen and will no doubt grow.

The D. C. amplifier used for intracellular recording usually needs to be of relatively low sensitivity, 50 mv./inch being adequate in the lowest range but, in order to study the smaller prefatory or after potentials, amplifications 10- to 100-fold higher sometimes prove necessary. This range is not difficult to attain and, for the lower sensitivities, the preamplifier then serves chiefly as a matching device for the input of the oscillograph. In many cases, the low sensitivity requirements lead to relatively simple conditions for drift and noise specifications. In a number of applications (FIGURE 5), however, long-term observations and measurements are necessary, and the drift needs to be made as low as possible. As noted earlier, values as low as 10 μv./min. have been attained.

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* A monograph on the cathode follower written by Doctor J. F. Toennies, but never published, which the present author read in 1936, described this application and its general theory.

† E. Amatniek, unpublished.

Special applications. More complex applications of internal and external recording techniques cannot be discussed here. Some of these applications are described in papers by Marmont,[14] Hodgkin, Huxley, and Katz,[15] Huxley and Stämpfli,[16] Grundfest, Shanes, and Freygang,[17] and Tasaki.[18] One problem that may be mentioned, however, involves simultaneous recording from a number of sites either in the body or from excised tissues with external or internal electrodes. The major problems involved are those of cross-coupling through common power supplies or common electrodes. A subsidiary problem stems from the lack of satisfactory multibeam cathode-ray tubes. As may be seen in FIGURE 2, even a single-gun tube may have severe distortion over a rather large part of the screen. In multibeam tubes there are added to this distortion others introduced by the geometries of the guns and by electrostatic interaction of the elements. Multiple recordings (FIGURE 6) are becoming more useful, and some consideration should be given by the engineer to this problem by designing either better multigun tubes or good high-frequency electronic switches.

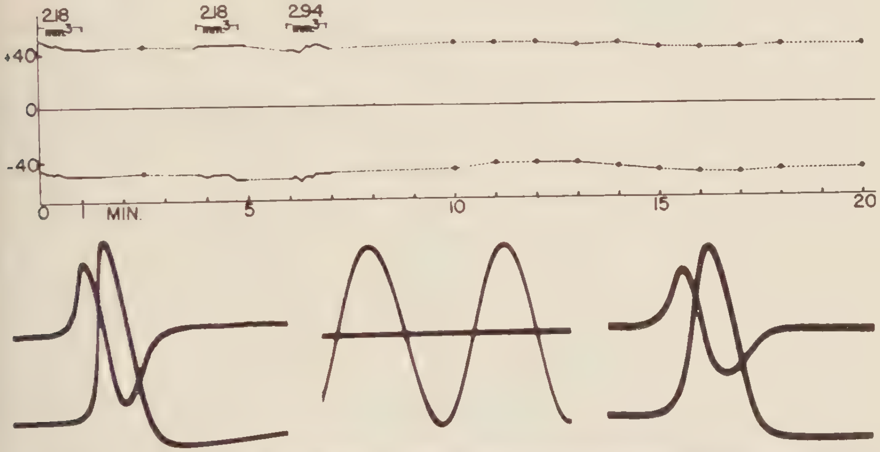

FIGURE 5 Long term recording with a D.C. amplifier. An intracellular electrode initially recorded the resting potential and spike shown in the lower left record. On the zero potential base line is the propagated diphasic response obtained simultaneously with external recording electrodes, at high amplification. The record in lower right was made 20 minutes later. Time and amplitude calibration, 1000 c.p.s. and 100 mv. The graph shows the resting potential (inside negative, and the peak of the spike (positive) during the course of the experiment, which involved three microinjections of KCl in the early part of the sequence.[23]

Requirements Associated with Photography

Photographic recording of oscillographic presentations is almost universal. The range of sweep speeds is wide (FIGURES 6 and 7), and changing from one to another requires adjustment of the beam intensity. At the present time,

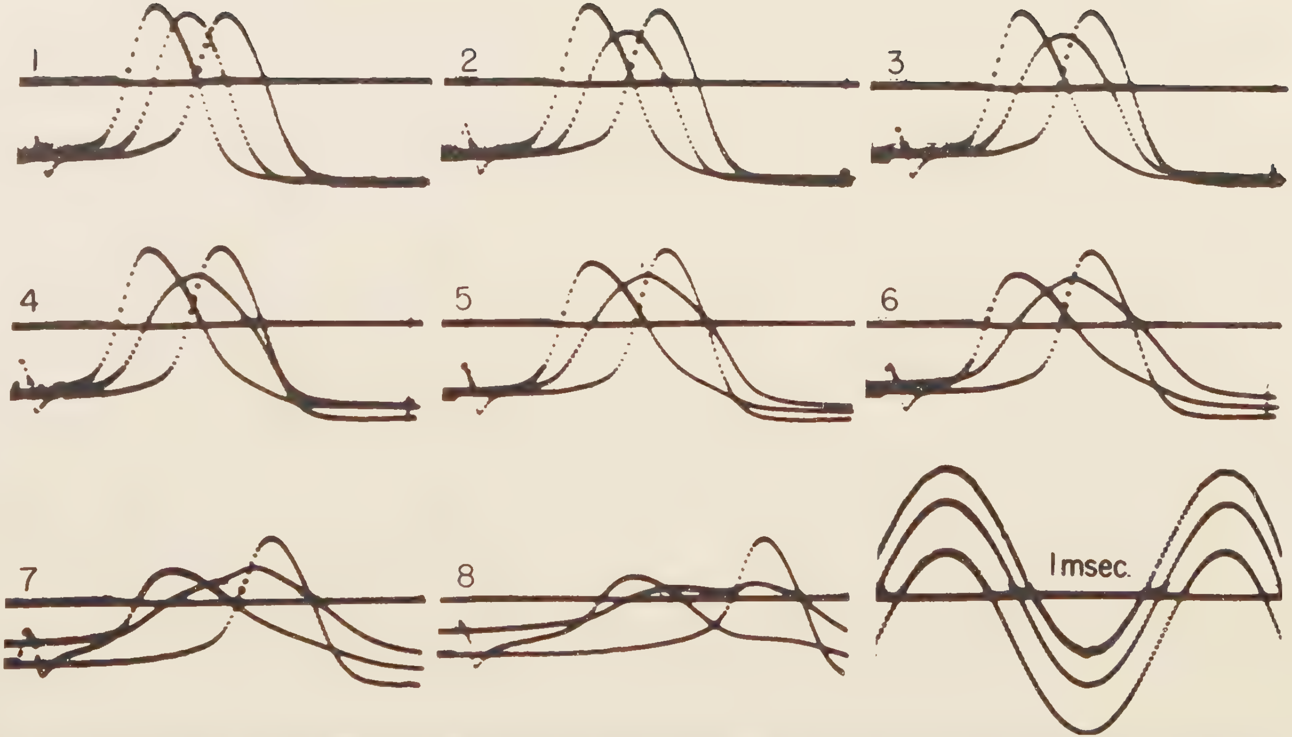

FIGURE 6. Simultaneous recording of propagated activity in the giant axon of the squid, *Loligo*. The records were made with three electrodes inserted into the axon. The two traces of a dual beam oscillograph were split by electronic switching at 100 kc. to provide the four recorded lines. The experiment represents the changes in form of the spike produced by localized microinjection into the axon in the region of the central recording site. The spike at this region altered in amplitude and form (records 1 to 3) before the responses at either end had been modified. Time and amplitude calibration 1000 c.p.s. and 100 mv. for the three active traces.[23]

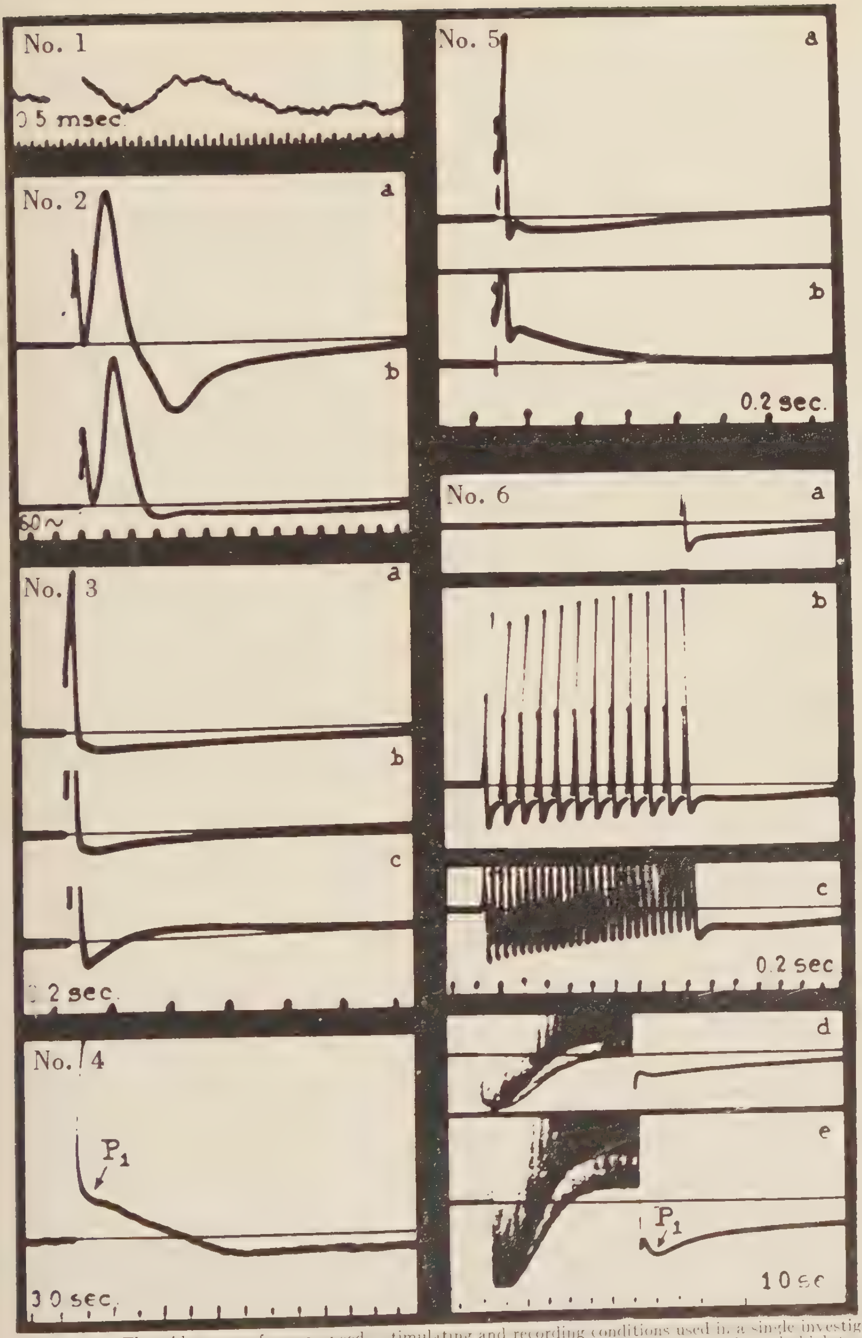

FIGURE 7. The wide range of sweep speeds, stimulating and recording conditions used in a single investigation. Recording of the single fiber spike of bullfrog C fibers required high sensitivity and moderately high trace velocity (1). The observation of very long time events (4) required about 3000 fold decrease in the trace velocity. The relatively long-lasting after potentials required use of a D.C. amplifier (2-6), but in most of the records at relatively low amplification, the spike in records 2, 3, 5 being several mv in amplitude, and these records showing changes in the form of the response under various experimental conditions. In No. 6, a single stimulus was delivered to the nerve (*a*) about 2.5 sec. after the sweep had started. The next record (*b*) shows a train of 12 responses at 7/sec. initiated about 0.5 sec. after the beginning of the sweep and terminating at the same time as did the single stimulus above. The start and end of the train was unchanged, but the frequency was increased to 15/sec. for 26 responses (*c*). The latter frequency of stimulation was maintained, but for about 7 sec. (*d, e*) and the amplification was doubled for the last record.[24]

this change is usually done manually according to the experience of the investigator. It would be convenient if oscillograph designers incorporated automatic level adjustment. Unfortunately, the range of trace velocities is so wide that electronic differentiating circuits to cover this range may prove difficult to engineer, but step adjustments of grid brightness, coupled to the step sweep frequency range switch might prove useful. Another and rather simpler problem would be to intensify the beam in proportion to its up-and-down deflections. The short pulses of the spikes, which tend to disappear when recorded on a slow, dim trace, could then be recorded satisfactorily. An associated problem is in the range of sweep velocities supplied in the packaged oscillograph. Until recently, this range has been insufficient at the low end, but, at present, this insufficiency is rectified in many of the later instruments.

Types of presentation. The discussion has thus far been concerned primarily with observation and recording of the single passage of oscillograph traces, since these are most commonly used. In some applications, repetitive exposure of the sweep beam on stationary or on moving films or paper are desirable (FIGURE 8). In other applications, the oscillograph spot is not swept, the time axis being provided by moving the recording material. There are relatively few cameras specifically designed for oscillographic purposes and, of these, only one known to me was designed with sufficient flexibility for the uses of bio-

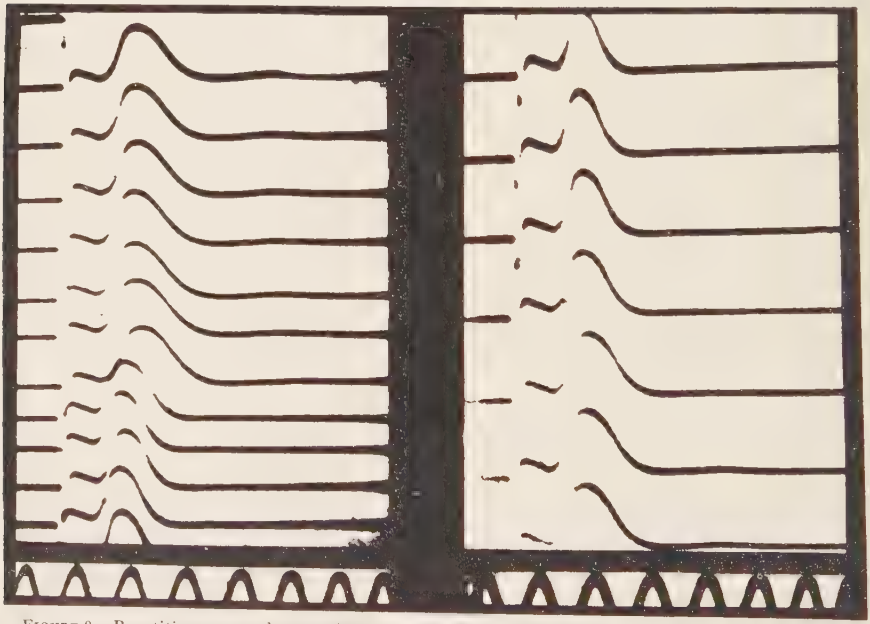

FIGURE 8. Repetitive sweeps photographed on moving film. The responses are spikes of a frog nerve stimulated at 20/sec. during sudden application (left) and sudden release of 7,000 lbs. hydrostatic pressure. Despite the vertical displacement of the film, the horizontal displacement was sufficiently rapid, as indicated by the 1000 c.p.s. time lines, to cause relatively little linear distortion. This instance is probably the earliest use of this method of recording, which takes advantage of the high time resolution of the cathode ray oscillograph while providing economical use of the recording material. This oscillograph presentation visualized about 15 per cent of the total time.[25]

logical recording. All these cameras, however, employ standard lenses and shutters, which would appear to be unnecessarily expensive. The screens of tubes designed for photography have relatively narrow spectral characteristics. Rather simple lenses, uncorrected for chromatic aberration, might prove adequate. Similarly, beam brightness gating circuits should be incorporated into all oscillographs. Complex short exposure shutters would then become unnecessary except when the tube face is photographed in high ambient illuminations.

In connection with the latter situation, another refinement might be asked of the electronic engineers. It is frequently desirable to monitor continuously the events observed on the tube face and to photograph these events either continuously or intermittently. Peepholes are inconvenient, as is working in a darkened room. Many users, therefore, are modifying existing equipment to incorporate two tubes in parallel, the one for visual observation and the other enclosed with a camera for photography. The modifications required for parallel operation are frequently major in character. Power supply limitations which will not support the drain of the additional CRT and of accessory circuits, and high-impedance output circuits which will not permit additional leads to the parallel tube have required, in our experience, major redesign in adapting packaged oscillographs for this purpose.

Stimulators

Stimulators for biological uses need to deliver pulses singly or in trains of variable frequency and duration. The amplitudes may vary in a range from 0.1 v. to 50 v. or more. Square pulses from about 50 μsec. to 50 msec. durations are easily obtained and seem to satisfy most requirements. Where repetitive trains are required, frequencies from about 1000/sec. down to 1/sec. or less are desirable. The durations of the trains are highly dependent on applications which have an extremely wide range of requirements. A useful and often necessary feature is the coupling of the sweep to the stimulus, so that either initiates the other after a variable time delay. In the stimulators used in our laboratory, this delay is variable from 0 to several seconds. Coupling of otherwise entirely independent stimulation channels, so that one starts with a controllable time delay before or after another, is also highly desirable. In stimulators, the functions of pulse duration, delay, repetition rate, *etc.*, are so different that individual circuit units for each of these elements may be packaged separately and stacked by the investigator to provide as many channels, with as much control as necessary for the individual purposes.

Coupling of the stimulus to the tissue through a circuit with very low capacity to ground is highly desirable, since this procedure minimizes the artifact produced by the often large common ground current from the stimulus. This end may be achieved by using low capacity transformers (*e.g.* GR Type 578) or R. F. coupling circuits.[19]

The output impedances of the stimulating circuit may be low to decrease loading, although some investigators prefer to use high-series loading to establish essentially constant current conditions. Others prefer to use constant current stimulus generators, but these generators usually have one side of the output at ground potential and therefore are not suitable for many purposes. It is questionable, furthermore, whether constant current delivered at the electrodes remains constant in the application to the tissue, since membrane properties of the active and inactive cells, as well as the electrode properties, may change during the stimulation. Fortunately, however, in most applications the problem of precise nature of the stimulus parameter does not occur. The control of relative intensity, its constancy at a given setting, and its adequacy for stimulation, under conditions that produce least disturbance in the recording system are the important determinants for most applications.

A design feature which is of general importance is that of the number of operating controls in the equipment, and it applies not only to the amplifier but also to the packaged oscillograph, to the stimulators, and to the combined equipment. Frequently, the investigator attempts what I believe is a false economy and forces this adaptation upon the designer. This tendency lies in the search for "universal" instruments. In the attempt to design such instruments, the engineer must cover extremely wide ranges in specifications, thereby making the equipment complicated to operate. A subsidiary effect is to make connections between the various units also complicated and "easily adjustable." A third complication results from engineering design itself. Often the number of controls to be checked or set makes the operation of the equipment unwieldy. In designing electrophysiological equipment, it is necessary to remember that biological tissues are relatively short lived. Difficult or intricate procedures usually consume a great deal of preliminary time. Failures of equipment due to overcomplex design or to poor construction are therefore inordinately wasteful, since a delay in operation for a relatively short time may cost all the preparative time. The strain that ensues when the investigator must constantly guard himself against turning the wrong switch or dial knobs of a complex array, or go through long procedures in checking connections or operating conditions is not conducive to good experimentation, and the engineer should try to minimize this disadvantage, even though the investigator may not demand this help.

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INSTRUMENTATION PROBLEMS ENCOUNTERED IN CLINICAL RESEARCH

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The current rapid development of improved instruments and new methods has been accompanied by a breath-taking expansion of the scope of clinical research. Today's cardiologist records pressure changes within the heart of an unanesthetized patient with greater fidelity than was possible for yesterday's physiologist to obtain from the femoral artery of an anesthetized experimental animal. These technological advances, however, have greatly increased the problems of the clinical investigator. It is no longer sufficient that he master the anatomy, biochemistry, and pathological physiology of the systems which he studies. He must now also be intimately acquainted with the construction and functional characteristics of the instruments that he uses for measuring or acting upon his subjects.

It is painfully obvious to those acquainted with the field that the training of many clinical investigators has lagged behind their technicological requirements. Before setting up an experiment that involves the measurement of a pressure, the investigator must answer such questions as: "What sensitivity is required?"; "How great a range of pressure must his transducer follow?"; "What are the tolerances of his problem regarding long-term stability, short-term stability, frequency response, and pressure-volume displacement ratio?"; "Among the available commercial transducers is there one suitable for his problem?"; "Will operation of the new equipment cause interference with other parts of his experimental system?"; "Does he have facilities for maintenance and repair of this equipment?" Many investigators not only do not know how to answer such questions, they are frequently unable to express their problems in meaningful questions.

If the clinical researcher is to do a satisfactory job, he must have help to cope with his engineering problems. What kind of help does he need? This problem can be dealt with by considering some of the questions which he asks. The following are typical examples:

"I want to measure cardiac output during surgical operations. What methods are available for doing so?"

"I have equipment designed to measure arterial blood pressures. I now want to measure pressure changes in the anterior chamber of the eye. Is the equipment I have at present suitable for this job? If not, can it be modified to make it suitable?"

"I am setting up a cardiovascular laboratory and have limited funds with which to equip it. What particular pieces of apparatus should I buy so as to get the most function for my money?"

"I want to measure respiratory flows of anesthetized patients. Does anyone make an explosion-proof pneumotachograph which can be incorporated into a closed rebreathing system?"

These questions reflect problems in communication and may be grouped in two categories. The first query comprises problems in semantics. The investigator needs help in interpreting his requirements into terms intelligible to the engineer. The second category involves the transmission or dissemination of information. The investigator needs help in directing his problem to the most appropriate instrumentation scientist. The instrument maker also needs help. He must keep informed of what the biologists are attempting to do, so that he can design to their requirements, and he must then be able to make the biologist aware of the usefulness and availability of his new instruments.

What sources of help are available to the clinical researcher? The investigator with adequate funds and space facilities, of course, can hire and support his own staff of engineers. This procedure is an ideal working arrangement. The individual who is working in a large medical center or university hospital may find it convenient to seek advice and information from colleagues working in basic science departments and in other laboratories around him. Unfortunately, the largest number of patients eligible for clinical studies are not treated in the large medical centers but are treated in the smaller 100 to 300 bed nonprofit association hospitals, which have neither the basic scientific staffs nor the facilities for hiring engineers. Technological deficiencies alone do not seem ample justification for rejecting this vast source of clinical material which is otherwise available for study.

Apart from his immediate environment, what other resources of information are open to the clinical investigator? The instrument journals are available to him through libraries, but many of the articles in these journals are written by instrumentation scientists for instrumentation scientists, and are unintelligible to the average clinical researcher. The latter may refer to such excellent reference series as *Methods in Medical Research*, but such volumes usually treat problems in a general fashion, and the answers to specific questions arising during a particular project may not be discussed.

The investigator is afforded access to the representatives of instrument manufacturers at his scientific meetings and conventions. The people with whom he may discuss his problems in such circumstances, however, have been selected primarily for their selling ability and only secondarily for their knowledge of engineering. If the researcher is sufficiently astute to recognize this fact, he may request, and may be granted, consultations with members of the engineering staff of the instrument companies. These people, however, are trained in the fields of engineering, and they have less acquaintance generally with the problems with which the biologist is concerned than the biologist does with engineering technicalities. As a result, the engineer finds it difficult to understand exactly what the investigator requires.

The clinician can also study the advertisements of the instrument manufacturers, and he can request brochures for more detailed descriptions of the instruments in which he may be interested. Again, the type of information given in such brochures usually is presented in a terminology which will not tell him whether the instrument is suitable or unsuitable for his particular problem.

Having pursued all of these avenues and still having only a hazy idea of what he needs, the clinical investigator, in desperation, may buy an instrument which he *hopes* will do the job. More frequently than not he will be disappointed. The instrument either will be inadequate in one or another aspect, or it may require modification before it is suitable for his purposes. Having invested a large fraction of his available funds in the instrument, the investigator does not feel free to set it aside and try another potentially more useful model. Or, if modifications are required, he may find that he must seek more funds to finance the modifications, or he may have difficulty in locating appropriate facilities for performing the modifications.

The purpose of this presentation is to consider a plan which may effectively and efficiently provide a solution to the problems of communication which, at the present time, hamper the field of clinical research. When the chemist is faced with a reaction which fails to proceed toward the predicted synthesis, he provides a catalyst, that is, an intermediary agent compatible with both reactants, which serves to accelerate the reaction toward completion. It is suggested that an appropriate catalyst for the problems in question would be an advisory body constituted of experts trained in both biology and engineering. Such a group could answer questions of "How to do it?" and "Where to find it?" or at least offer the best educated guess. Such a group could serve all groups interested in biological instrumentation, including researchers, designers, and manufacturers.

Who is to serve on the proposed advisory committee? It should be possible to gather a sufficient number of informed individuals from the various special fields of biology and instrumentation to make it unnecessary for any single individual to give more than a few hours of his time each year to discharge the duties of the group. These individuals should be solicited from the more successful laboratories of universities, hospitals, and research institutes, and from instrumentation laboratories in industry and government. Service on the committee should be by appointment. Appointments should be made for specified periods. The work of the committee should not require removal of its members from their own laboratories, except perhaps to attend an annual meeting.

How would requests for advice be channeled to the appropriate experts? A central office would be established with a staff equipped to screen and direct inquiries to appropriate members. A file listing the fields of interest of each committee member would be used as a guide.

Who is to support such an organization? One of the obvious problems which might arise in the regulation of such an organization would be subversion of the primary aim of disseminating information to the personal aggrandizement of an individual or group. The produce of a particular manufacturer should not receive undue emphasis, nor should that of another receive undue criticism. Potentially patentable ideas entrusted to the group should not be circulated indiscriminately. Thus the group must be governed by a body sympathetic with the aims of the project, but in no way dependent upon its activities.

A body satisfying the above criteria might be derived from one of the foundations interested in medical research; from a professional society such as that which has so generously sponsored this conference; or from an agency of the government such as the United States Bureau of Standards or the National Institutes of Health. The money required for establishing the organization and for maintenance of the necessary secretarial and communication facilities might be solicited from one of the above agencies, or from the instrument industry itself. In the latter case, the prerogative for administration of the funds should be surrendered to the governing body.

Could the activities of such an organization justify the cost of supporting it? Besides offering help frequently unobtainable through other channels to individual experimenters, the organization could be of value in other ways. Such a group could be of assistance to the instrumentation scientists by clarifying the requirements of various biological fields, and to the instrument manufacturers by establishing standard specifications for various catagories of instruments. Through normal intercourse within the group, solutions to instrumentation problems of one field of research would tend to be found in the solutions of other fields having similar requirements. Furthermore, in its capacity as an informal clearing house for new projects, it might help to coordinate the activities of unrelated groups having similar interests and, on the other hand, would serve to forestall needless duplication of effort.

Many problems would be involved in the initial formulation of the organization. In regard to the preparation of the central office, would an instructed secretarial staff be adequate to channel the inquiries, or would professional personnel be required? It must be decided whether the office should serve simply as a clearing house for correspondence, or whether it should have correlating functions on a professional level.

How is the file to be acquired? Possibly the "register of scientific and technical personnel" maintained by the National Science Foundation could serve as a source of information on potential advisors' interests and capacities.

How many qualified people would be willing to serve as advisors? What inducements should be offered to attract capable members? Should a retaining fee be granted with each appointment, or should service be expected on a volunteer basis? A questionnaire directed to potential members during the initial phases of organization might supply the answers to these questions.

Who will undertake the original organization of the group? This job, without question, will require great tact and persistence, and a deep understanding of the problems involved.

The magnitude of the task of initiating a service organization of this nature cannot be minimized. Nevertheless, the compensations to be derived from such an organization would more than justify the efforts required to establish it.

This scheme is suggested, not necessarily as the best way to solve the problem, but rather to call attention to the importance of the problem and to indicate that a solution is possible.

GENERAL AND SPECIFIC PROBLEMS INVOLVED IN DIAGNOSIS AND RESEARCH BY MEANS OF ELECTRONIC INSTRUMENTS IN A LARGE GENERAL HOSPITAL

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In the past 25 years, there has been an extraordinary growth of the application of electronic instruments to the diagnosis and clinical investigation of medical problems in large general hospitals. Actually, there are two main groups of electronic equipment that function in general hospitals or teaching centers. The first group consists of commercially available equipment of all sorts that is in wide routine use, and the second consists of equipment that is both experimental and new and not in common use at the present time.

(1a) The first group includes such apparatus in communication as public address systems for calling doctors, whether these appliances are in the form of telephone lines or short-wave radio, and various types of recording and statistical machines, such as electric typewriters, computors, dictating equipment, *etc.* Here the electronic equipment is widely available commercially, and the various outlets for the manufactured products maintain a close and efficient service and repair department. Thus, the staff of the hospital is not concerned about maintaining and keeping the equipment in operation.

(1b) Also included in the first group is the diagnostic medical equipment in which electronic instrumentation performs an essential part. These are items such as audiometers, electrocardiographic apparatus, special X-ray equipment, colorimeters, electronic monitored basal metabolism machines, *etc.* Electronic apparatus used in treatment such as diathermy, physiotherapy light and heat equipment, muscle stimulators, *etc.* should also be mentioned. These appliances are also widely available throughout the country and are adequately serviced through their sales representatives, so that physicians have little trouble in seeing that they work.

(2a) This group, however, opens up the first major instrument problems so far encountered. In this group, there is equipment manufactured over the past 10 to 15 years, in use in most general hospitals and available throughout the country, but not, as yet, included in the efficient service and maintenance organizations characteristic of the previous group. This equipment includes electroencephalographic equipment and electromyographic and similar recording units for other biological phenomena, such as eye potentials. These appliances are usually produced by competent electronic engineers who have developed them through their experimental stage and have organized companies which produce and sell them throughout the country. These companies, however, are not large enough to maintain agents and maintenance personnel in all large centers. They make it a policy to cover their maintenance by sending around experts who tour the country perhaps once or twice a year. A few of these companies have electronic engineers available locally, but these sources are very unstable and erratic. Most large institutions using this type of equip-

TABLE 1

ELECTRONIC APPARATUS PRESENTING NO PROBLEMS

Intercommunication systems
Statistical computors
Dictating equipment
EKG
X ray
Radiation scalers
Electronic colorimeters
Spectrometers
Photography aids

ment have to develop servicing facilities of their own. Among the manufacturers of this equipment there may be a certain amount of reticence and unwillingness about having too many different persons represent them for maintenance and service, as some of the circuits and details of their mechanical operation are still uncovered by patent and are subject to being copied by others. This situation, when a major breakdown occurs, throws on an institution the burden of sending the old unit back to the manufacturer, which may result in a delay with no operation lasting as long as three months. Where the manufacturer is located in the same community as the institution using the equipment, the problems of repair do not produce any serious situations of this type. This situation occurs in only one per cent of the cases.

In this same group of instruments there are also a series of foreign units coming from Denmark, France, England, and Germany. Here the delay in maintenance and service problems is complicated by the impossibility of obtaining a replacement part locally. In many cases, the situation becomes so hopeless and impractical that the apparatus is abandoned. Most laboratories faced with this problem on a large scale solve it *partially* by the employment of a part-time or full-time electronic engineer who has to learn, through a process of trial and error, the technique of repair and maintenance of the equipment. Some of these units do not have complete instruction manuals, wiring diagrams, or complete lists of component parts, which makes the problem of repair more difficult. The cost in both time and money due to this situation, in some hospitals or institutions, may be several times the initial cost of the equipment.

(2b) A second part of group 2 includes a special research type of diagnostic equipment used either in clinical investigation or laboratory study on animals. This material is not available through the usual outlets and is usually made individually for the investigator from parts of available equipment such as oscillographs and amplifiers. Maintenance and repair of this equipment require absolutely that an electronics expert be available.

TABLE 2

ELECTRONIC APPARATUS PRESENTING SOME PROBLEMS

EEG and EMG apparatus
Electronic transducers
Electronic stimulators
Stroboscopes

Table 3

Electronic Apparatus Presenting Perpetual Problems

Wave analyzers
Toposcopic displays
Ultrasound scanners
Neutron scanners
D.C. amplifiers
Special recorders

The development of research equipment for the investigation of clinical phenomena such as the localization of intracranial tumors by the use of neutron scanning devices is usually integrated with an adequately trained consulting physicist or electronic engineer in the original project. The preliminary results are, therefore, under adequate control as far as maintenance and service are concerned. However, as soon as the material is presented before a medical meeting and published, other hospitals or centers who wish to do similar studies find that there is no way that this end can be accomplished satisfactorily. The developing scientists in the first institution are justifiably unwilling to go into commercial production to service another institution, and the equipment is sufficiently complicated and expensive not to interest a well-established commercial concern. The same thing may be said of the very complicated display systems for the study of both heart and brain waves and the various kinds of automatic frequency analyzers of brain waves.

Part of the difficulty that is encountered in institutions that wish to encourage new developments in modern equipment and clinical investigation of all types is the lack of understanding on the part of the clinical investigator as to the best kind of equipment and electronic apparatus that should be used in the project. Very often a group of clinical investigators will be badly advised, so that an expensive and complicated piece of equipment is purchased to do something that could be achieved by a much simpler technique. Their budget is then overburdened by both the maintenance and initial outlay for such equipment, and frequently the apparatus is abandoned and left unused because of the excessive demands made to service and maintain it properly. For example, a clinician interested in the study of epilepsy who was competent to supervise and maintain an electroencephalographic laboratory using the conventionally available apparatus wished to enlarge the scope of his study by including automatic frequency analysis of the recordings of some of his cases. He did not have the facilities, however, to maintain, repair, and operate such complicated equipment, so the result was that he lost most of the initial outlay of $5000 and two years' time, and was never able to get satisfaction from the equipment. It would have been far more practical, in his case, to have trained a competent assistant or technician to do the frequency counts of his tracings manually, as has been done in many similar situations.

A great deal of the difficulty encountered in maintaining and repairing, as well as in servicing, of electronic equipment in hospitals in the second group of categories mentioned is due to the ignorance and inexperience of the sponsoring physician in the nature and fundamental background of this equipment in relation to his problem. For example, if a neurologist wishes to purchase a cathode-ray oscillograph for the recording of muscle potentials, he finds that there are a half-dozen commercial units available with different characteristic properties and complications. The proper preamplifiers and photographic equipment that are necessary vary equally. The whole subject is confused by prejudice or ignorance, as well as by the unfamiliarity of the electronic expert in the application of this equipment to the problems of the neurologist.

The problem that confronts the physician doing clinical investigation and the engineer can be shown in the following example:

In the study of patients with Parkinson's tremor we wished to measure visual motor-reaction time. The usual technique for this measurement includes a key that the subject presses at the exact moment he sees a visual signal, such as a flash of a neon lamp. Both the time that he presses the key and the time that the lamp is turned on are recorded on appropriate moving paper or film, and the distance in time between the two marks gives the motor-reaction time. In the case of patients with severe tremor, such a system is impossible because the shaking finger would erroneously touch the key and give a false signal.

An electronic design engineer was consulted, who spent several weeks on the problem. His solution involved a series of feed-back circuits which would close the signal system for tremor movement of a certain type, but allowed a specific pressing movement of the fingertip to come through. The cost of designing and building such a unit was estimated at between $600 and $700.

Meanwhile, the investigator lost a bet involving his trying to pinch between his finger and thumb a crisp dollar bill that was dropped to the floor and was to be grabbed before it passed through his fingers. It was obvious that the little trick involved a nice measurement of visual motor-reaction time; the bill, being 12.5 cm. long and falling according to the formula of gravity, covers this distance in 0.16 seconds, therefore falls just a bit faster than the reaction time. Because of this information he provided a longer falling body—a flat aluminum strip 4 cm. wide, 2 mm. thick, and 46 cm. long. It was light enough to be caught and stopped by finger pressure, and at normal reaction times of .18 to .25 sec., fell 16 to 30 cm. respectively. Using the falling-body formula, the bar was marked in fractions of a second from .12 to .31 at its end. This bar could be dropped between the finger and thumb of a patient who was shaking quite severely, who would then grab the bar in its flight as soon as he could, and the distance along the bar would give the exact fraction of a second involved in the reaction time. This time was calibrated against the usual apparatus and found to be equally accurate, and the problem was solved at a cost of only a few dollars.

Suggestions. It would be most valuable in every large university or other teaching center, where this problem arises, to have a group of consultants who could be brought in from the outside, if necessary, to scrutinize all research of laboratories that planned to purchase electronic equipment and advise as to the most practical type of equipment to secure and what the complications of maintenance and service might be. Such a board should consist of an electronic engineer familiar with medical problems of investigation, an expert instrument designer, a medical expert who has used electronic equipment in the past, and possibly a statistician who could point out the necessary limits of accuracy required for the project.

Another suggestion would involve annual meetings of large scientific societies where papers are reported on by investigators of biological problems, some of them involving electronic instruments. The last half-day session of such a meeting could be devoted to brief reports on anticipated research where special apparatus is to be built or procured. Electronic engineers and instrument manufacturers and designers could be present at such a meeting and participate in the discussion and suggestions that would come up with each problem presented. In this way, a great many wasteful and unsatisfactory experimental ventures could be eliminated. The chance of valuable equipment being properly procured by such investigators would be increased. Those who are unwilling to share their contemplated investigations would not be interested in this session.

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INSTRUMENTATION REQUIREMENTS IN SENSORY AIDS

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Introduction

In recent years, considerable effort has been made to apply engineering techniques to the development of devices intended to alleviate some of the handicaps of loss of sight and hearing. The development problems are unique.

In the field of guidance devices for the blind, for instance, one starts with a conviction that some sort of instrumentation is required. Often one is not quite sure what should be measured. When the measurement has been made by the instrument, there arises the important and difficult question of how to impart this information to the user. Having made decisions on these and other points, a test instrument may be designed and built. Then comes the not-too-easy task of determining in what way and to what extent it serves the intended purpose.

Thus, instrumentation development in this field poses some unusual problems in addition to the expected technical ones.

Nowadays, it is commonplace to see hearing aids in use. Not so many years ago, the ear trumpet was used by those whose sound perception had lost sensitivity. Today, great amplification is possible with small electronic devices requiring relatively little power. Progress has been made in fitting the hearing aid to the hearing loss of the user.

Much less common, however, is the work which has been done to help those who have lost either all or so much of their sight that ordinary refractive correction is not the answer. In this field, work is still in an elementary stage, and continues at a low level compared to efforts in the hearing-aid business, where, unfortunately, success in sales sometimes depends more on the choice of a good advertising agency than upon a competent technical staff.

Consider now the basic principles to be kept in mind in the selection and development of a sensory aid.

When the impaired sense has some function remaining, it should, if possible, be used. A sensory aid is a device for communicating information. The port used for the entry of the information, if other than the original channel, may be overtaxed by the extra burden. After all, when one sense is lost, the others usually will be put to greater use. In addition, there is frequently satisfaction for the individual in continued use of the impaired sense. As long as the loss of function is not total, there may not be feeling of being seriously handicapped, and adjustment may be easier.

When there is complete loss of sight or hearing the problem is different.

Restricted Information

Strangely, one of the principles most often overlooked by the engineer is that the sensory aid must not give too much information, in the case of loss of sight, at least. The details of presentation have a great effect in determining how much information can be used. Instruments which seemed desirable because they appeared to give so much of the information normally secured through the lost sense have turned out to be unworkable in practice because the individuals using the devices were confused by too much information. In some instances, the information could be absorbed for a while, but the strain was great and, eventually, frustration resulted.

People differ in ability to master new means of data presentation and in the rapidity with which they react. Most persons, however, are not as intelligent and patient as many research workers seem to believe; or perhaps it is not a matter of intelligence but of learning to act quickly on an output of data that tries to substitute for the enormous information-gathering power of the eyes.

The sensory aid is never a perfect substitute. The engineer working with sensory loss is very soon impressed with the information-gathering capacity of the eyes and ears, and the ease with which very complex data are used as a basis for decision. It is exceedingly difficult to devise practical inanimate devices which in any way approach this performance. The sensory aid cannot fully make up for the lost function, except where there is just some loss of acuity. A good amplifier may almost restore hearing efficiency. Spectacles may almost restore visual acuity. A magnifier may almost restore visual performance for reading but is not good for distance.

Consider the problem of guidance devices that are intended to make travel without sight safer and easier. For proper development, it must be determined what information is wanted. No device will provide all the knowledge obtained through the eyes. The decision may be that it is very important to detect obstacles in the path, preferably at least six feet ahead. Or it may be decided that the guidance device must detect large and small downward discontinuities such as curbs, cellar ways, and open manholes. These must be known far enough ahead to permit corrective action to be taken.

Another objective of a guidance device for the blind may be to give information that will permit a pedestrian to select an efficient path through a maze. A practical maze is a sidewalk with houses and their steps on one side, a curb on the other and ash cans, lamp posts, trees, toys in between. If an obstacle locater alone is used, and is merely an on-off device or has very short-range, then the user is very likely to bounce from one obstacle to another and his path will be zigzag. To proceed efficiently and to identify his destination, he needs enough information about his surroundings so that he is well oriented with respect to them.

Some guidance devices sample the environment in very small stages. For instance, one group of obstacle-ranging devices that, incidentally, have been successful for a number of people, projects a light beam about two inches in diameter and gives, by touch or sound, a signal which tells how far the light beam travels before being reflected by an obstacle. Thus, the kind of information received is very much like the kind of information which a sighted person gets by walking on a very dark night using a narrow beam flashlight, except that the sighted person gets additional clues from color and texture.

It is easy to see that any guidance device which attempts to give all this information through any channel other than the eyes may provide safety in travel, but certainly not high speed. The limits of performance are not the engineering ones of developing the sensing apparatus, but the psychological ones of developing adequate means of transmitting the data.

Upon consideration, it becomes apparent that the simple cane has many advantages as a guidance device for the blind. Not only is it inexpensive and convenient to lean upon in case of fatigue or misstep but, despite short range, the cane inspires some confidence as well as imparting much information through physical contact with the environment. For some reason or other, we are more confident when we can actually touch or see our environment. The nearest thing to touch by hand appears to be touch with a solid physical extension of the hand, such as a cane.

In the development of these devices, we should not be afraid of new concepts, like the detection of obstacles by characteristic shadows; or of very simple devices such as an audible clicker, which sends out a directed sound so that the echo can be used with the unaided ears in obstacle location, or of the old tried and true cane, referred to above. Perhaps the net result will be a combination of several approaches. A study of the performance of other devices should yield valuable information on which to base further work. Frequently, hindsight indicates that the fundamental premises of earlier developments were erroneous. Unrealistic performance was considered desirable because too little was known at the time about human capacity and limitation.

If limited functions are required of the device, the engineering difficulty of satisfying the requirements can be estimated.

Working out the Engineering Design

Frequently, it will be found, of course, that the desired characteristics are beyond the range of a practical program. Then compromises must be considered. These are compromises between the functions that can be performed, given no other limitations, and probable price in terms of size, weight, reliability, ruggedness, purchase and maintenance cost, learning period required, interference with other channels of information, *etc*. Having tentatively set an attainable development goal, this aim can be compared with the original specifications to determine the reasonableness of proceeding with the development and the likelihood that the proposed device will be of real value. In this evaluation, the sensory aid should be thought of in terms of the individuals expected to use it, not as an instrument to be developed to meet abstract specifications.

For example, the economic condition of the ultimate user is of utmost importance. If there is no hope of eventually producing the device at a cost which will bring it within the reach of those it is desired to help, the only assistance it can be to them is its evidence that "science" is on their side; or the device should be recognized as an intermediate development. Under many circumstances this recognition is enough. Basic research is indispensable to end-product development.

The vocation of the user is an important factor. The guide dog is a very successful travel aid for many of the blind; but in any number of jobs a dog cannot satisfactorily be cared for during the working period.

The guidance device may be used for purely recreational purposes. Finding the way around a golf course may present problems different from those encountered in finding the way to the card party.

The attitudes of the individual and the persons with whom he comes in contact bear heavy weight in determining the acceptability of any sensory aid. Considered merely as an instrument designed to make specific measurements and to transmit the information in intelligible form, a device may be perfect. If, however, its use attracts too much attention, or if the individual feels that it may make others consider him even more handicapped than he already is, there is a large additional problem. Time frequently brings more tolerant attitudes and acceptance of handicaps and devices to overcome them. Few of us are now reluctant to wear spectacles in public. More and more people are wearing hearing aids. This point has been brought home to us forcefully in connection with our work on the development of the sensitive cane, a traveling cane for the blind to which has been added electronic features to warn the user automatically of down-curbs, down-steps, and any downward discontinuity in the surface for faster, safer travel without fear of stumbling. For experimental purposes, auditory warning has been used. The sound has actually been generated in a small ear set worn on the ear or hooked on the collar. In numerous instances there have been objections both by the blind traveler and by members of his immediate family to the ear set because others might think it indicates some deafness. Of course, there are more obvious serious objections to an auditory signal in a device for the blind.

The physical environment in which the sensory aid is to be used may determine acceptability. The guidance problems of a blind farmer are different from those of the blind urban traveler. The pedestrian traversing short and familiar paths does not really face the same difficulties as one who explores new territory, as does a social worker or salesman visiting clients.

For even more reasons, the capacity of the instrument to convey useful information to the user in an unambiguous way is not enough. The training required to master the instrument may control acceptability. Relatively few individuals have the determination or the financial resources to undertake a long and arduous training program, despite the fact that the results may be very beneficial. Many handicapped people tend to stay at home and seek the protection of a sympathetic family. Quite aside from the fact that a period of training in residence may be just what is needed to promote rehabilitation, it does make a difference whether the instrument is one which requires relatively little disruption of normal living and can be self-taught through practice, or is one that requires a training course at some remote place.

The mental and emotional state of the individual will play a large part in determining whether he is ready to accept his handicapped condition and rehabilitation, including travel training. For some people, particularly older ones, it is out of the question to require them to leave their familiar surroundings in order to learn new skills. Many persons who lose sight or hearing never leave home. Others are determined to overcome their handicap and are willing to go to almost any lengths. The sensory aid must be considered in terms of how easily it can be mastered.

A number of people with sensory loss are also victims of other physical disabilities, because of accident or disease. Their physical conditions may determine some of the characteristics of the sensory aid which they can use.

Suppose a sensory aid development program is under consideration. It may be decided that a new instrument should be developed in order to give information somewhat different from that provided by other devices. The emphasis may not be on the kind of information, but rather on the way in which it is presented. Herein is the crux of the problem—providing adequate information in an intelligible way, but in a way that is neither distracting nor fatiguing.

It has been suggested that, in deciding whether a particular path of development should be followed, thought should be given to such characteristics of the device, when developed, as the probable cost, size, weight, interference with other senses, tolerability, conspicuousness, *etc.* Any one of these factors, if out of line, may completely outweigh the advantages. Our experience has been that handicapped people make an over-all judgment of the value of a sensory aid. In this respect, they are like most lay persons. Apparently there are very definite limits for acceptability, connected with a number of the important characteristics. If the proposed new instrument is likely to exceed the limit in any one particular, its performance must be excellent if wide acceptability is to be achieved.

Rough estimates of the direction and limits of a development can be made, based on past experience. We are not considering basic research programs leading into entirely unfamiliar territory, but rather the application of already known engineering principles to a new problem. Failure to attempt to judge the feasibility of a sensory aid development before starting actual development work omits a very necessary step. It not only deprives those interested in the development of a proper basis for appreciating the promise of the program, but also leaves those doing the job without definite goals toward which the work should be directed.

The development of sensory aids for the visually handicapped, during and immediately after World War II, showed that engineering techniques had advanced to such an extent that it was possible to devise new instruments that showed promise in this field. The state of the art in physical science, however, apparently was far ahead of knowledge about human psychology relating to these problems. No one seemed really to know what information the handicapped needed. Although a number of papers had been written relating to the ability to absorb information through channels other than eyes, these data were not extensive enough to be too helpful in devising stimulators for guidance devices. It is still true, in the main, that engineering specifications cannot be properly written because of lack of biological information. Feasibility could be determined only for the engineering aspects. Usefulness as sensory aids was much harder to predict.

Thus, it may be necessary, in the development of a guidance device or other sensory aid, to conduct concurrent research in order to examine critically some of the propositions about desirability of information and modes of presentation. The problem of applying these research results to the actual device situation should be made as simple as possible.

Once it is decided that there is justification for proceeding along new lines, technical development may follow. This plan is carried out in this field in much the same way as other technical development. An attempt is made to analyze the whole problem and to break down the over-all objectives into manageable tasks that can be separately attacked. Then the solutions can be applied to the main objective. In sensory aids other than amplifiers, interest is first and foremost in deciding what kind of information the device will present: *i.e.*, What will it measure and how will it stimulate? A guidance device, for instance, can measure the distance to the nearest obstace, or it can measure how much of a discontinuity exists in the road surface ahead. Equally important to decide is in what way the information will be presented. It is quite possible to have in mind several alternative modes of data presentation, such as the use of tactile, electric, or auditory stimulation. The experimenter, however, should have a good idea of just how well a person can use various signals and what his tolerance is for the signal. Information to be presented by auditory means can be rather complex and yet easily interpreted. Auditory signals to the blind, however, tend to rob them of the tremendous amount of information which they normally received through their ears. Tactile stimulation may be at a point or spread out. Discrimination is not nearly as fine as with the ears, and learning to react to any but the simplest signals represents a formidable challenge. Interposed between making a measurement anc presenting the data is the instrument. The device, of course, must satisfy the functional requirements of instrumentation. It may present raw data or it may process the data. It may be an on-off device, or it may give a large range. It must also be an acceptable piece of equipment for the individual to use. This acceptability depends on many things. The relative importance of the several factors will vary from individual to individual, but none can be ignored. If a firm decision can be made concerning what is to be measured and how the measurement is to be conveyed to the individual, then the remaining problems are straightforward. Usually, of course, compromises must be made all along the line in order to permit development within the physical limitations that are imposed.

Field Evaluation

Once a prototype has been produced, field tests are necessary for evaluation. During the whole course of development, experimentation on various features may be necessary but, despite the fact that the individual components appear to be acceptable, it is not reasonable to assume that the final device will also be acceptable. Cases may be cited to show that devices were unacceptable, even though based on principles that were thought demonstrated by experiment to measure the proper quantities and to present the information in acceptable form. For instance, if a blind pedestrian is given a guidance device that gives, in intelligible form, enough information to permit him to select a proper and efficient path safely and without tension, the device is still of no immediate practical value to the blind population if it requires 100 pounds of equipment and ten dollars a day maintenance cost. A simple wooden cane is better. This example, of course, is overdrawn, but there are many subtle features, such as balance, the reaction of friends and strangers, training required, whether or not the device feels safe, that influence final judgment. Some of our cooperating test subjects reported, regarding our sensitive cane, that there is just nothing to do with it in a crowded street car or classroom. While this may seem like an extraneous comment, it may be significantly disturbing to the individual, particularly if he has had an unpleasant experience with it. In a field-test program, it is not enough to ask test subjects what they think. It is highly desirable to try and get as analytical a reaction as is possible, but many people are not very analytical in their response or their thinking, and frequently are not frank. They try to be helpful and encouraging, but fail to report that they are really dissatisfied with something upon which they know you have spent a great deal of time and effort. They are likely to say what they think you would like to hear. Over-all acceptability or rejection must be measured by finding out whether or not the device is being used when there is a free choice.

Of course, each experiment and each device, whether it is accepted or rejected by the handicapped, should add to the store of knowledge about sensory aids and should make possible a better job the next time.

It may not be easy, however, to determine accurately which features are good and which are not. What is good for one person, at one time, may not be good for the same individual under different circumstances, or for another at any time. Frequently, it is possible to check some reactions by changing test instruments in one way at a time, and then resuming the tests. This recourse may show that the test subjects are not clear in their analyses. They do not want what they thought they wanted.

It is very difficult to get clear indications, when there are distractions such as instrument malfunctions or annoying details, such as poor balance, excess weight, too much noise, *etc*. Such distractions upset the judgment of the test subjects.

The experimenter must be understanding and have good intuition, to say nothing of good luck.

Summary

Thus, we may realize that instrumentation requirements in sensory aids not only include many factors present in laboratory or industrial instrumentation but, in addition, include a number of considerations that are unique. These problems arise because the instruments are never a final answer, because the devices must be closely integrated with actions of the people using them, and because of the great influence of factors of psychological and sociological nature over which the research worker has no control.

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Part III. Some Examples of the Use of Analog Instruments

AN ANALOG COMPUTER FOR STUDYING BIOLOGICAL SYSTEMS*

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Introduction

Computing machines are rapidly becoming an important tool for scientists and engineers working in many different fields. In biology, mathematical analysis is being used more often, due to improved experimental techniques that enable biologists to measure more accurately dynamic characteristics of certain systems under controlled experimental conditions. Biochemists and biophysicists are trying to build mathematical models based on the fundamental principles of chemistry and physics to describe their experimental observations. In most of these cases, the variables observed as functions of time are related by a set of nonlinear differential equations which are not solvable analytically. The computer described was designed specifically to solve these types of equations. While this computer has been used mostly for the study of enzyme mechanisms, it is hoped that this report will stimulate the use of computing machines in other areas of biology.

Description of the Computer

The computer is an electronic differential analyzer using time as the independent variable and voltages as dependent variables. The operation units used are adders, inverters, integrators, and multipliers which give output voltages corresponding to the sum, inverse (multiplication by -1), integration with respect to time, and multiplication of input voltages, respectively. Also, there are potentiometers to multiply any voltage by a constant, and potentiometers to set initial conditions. Each of these potentiometers is operated between two unit-gain amplifiers which act as impedance changers and which also can be used as adders or inverters. At the present stage of development, there are 8 integrators, 7 multipliers, 14 adders or inverters, 8 constant potentiometers, and 12 initial-condition potentiometers.

Adders and inverters are conventional resistance-feedback D.C. amplifiers[1] which are constructed in a packaged form. FIGURE 1 shows the circuit of this amplifier. It has an open loop gain of about 600, and a bandwidth of 15 kc. Integration with respect to time is performed by a resistance-condenser feedback amplifier, shown in FIGURE 2. A balanced diode switch is used for clamping the integrator at the beginning of each computing cycle. Additional amplifiers are used following the integrating amplifier for setting in initial conditions and for gain adjustment. The multiplier which operates on the principle of taking the difference of the squares of the sum and of the difference of the input voltages has been described elsewhere.[2]

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* This work was supported by the Office of Naval Research, Department of the United States Navy.

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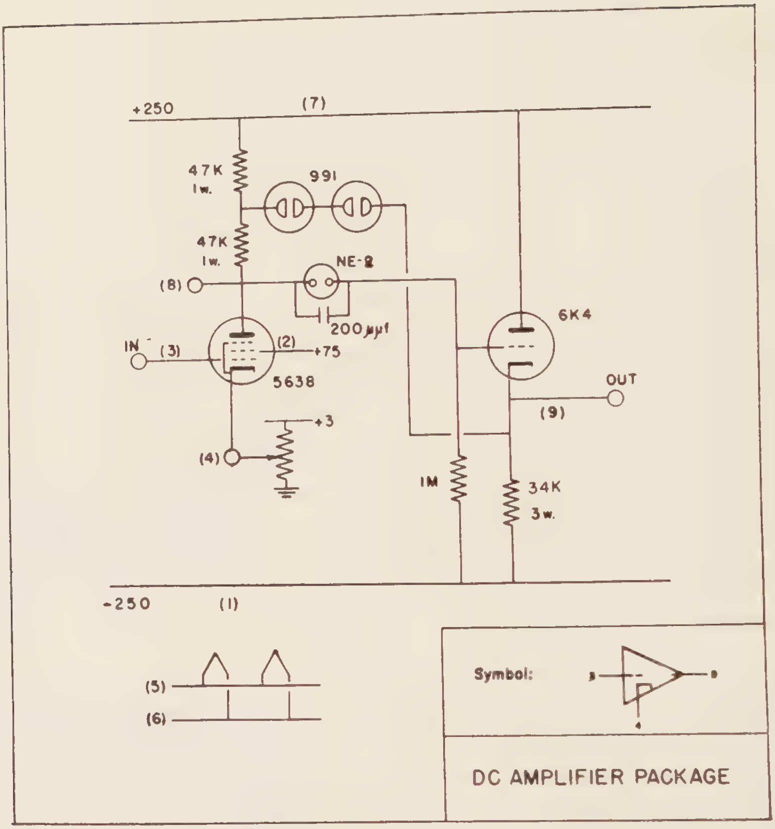


FIGURE 1. Circuit diagram of the D.C. computing amplifier.

To avoid the trouble of zero adjustments and drifting of the D.C. amplifiers used in those operation units, chopped D.C. voltages are carried through the adders and through the constant potentiometers. While the multiplier is actually capable of delivering a square wave voltage proportional to the product of two varying D.C. input voltages, outputs from the integrators are chopped before addition or multiplication by a constant. A detector is used to restore the D.C. level before the signal is fed to the input of an integrator. The chopping frequency used is 5 kc., which gives 300 points of computation in a period of 60 milliseconds. Both chopping and detecting are achieved by the use of diode switches as shown in FIGURES 3 and 4.

The computer is automatically programmed for fast repetitive computation so that solutions may be displayed on the screen of a cathode ray tube. The fast computing time enables us to survey rapidly changes in a particular solution resulting from a change of any constant in the equations. Thus, it permits a rapid comparison with experimental results in study of a proposed mechanism. A program unit is provided to supply both the switching and

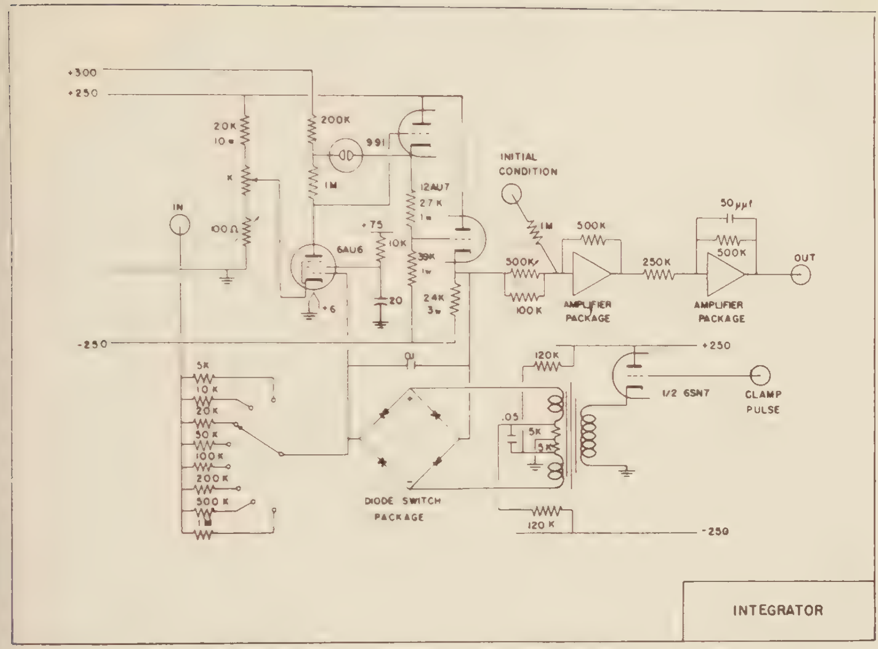


FIGURE 2. Circuit diagram of the integrator. The integrator also inverts.

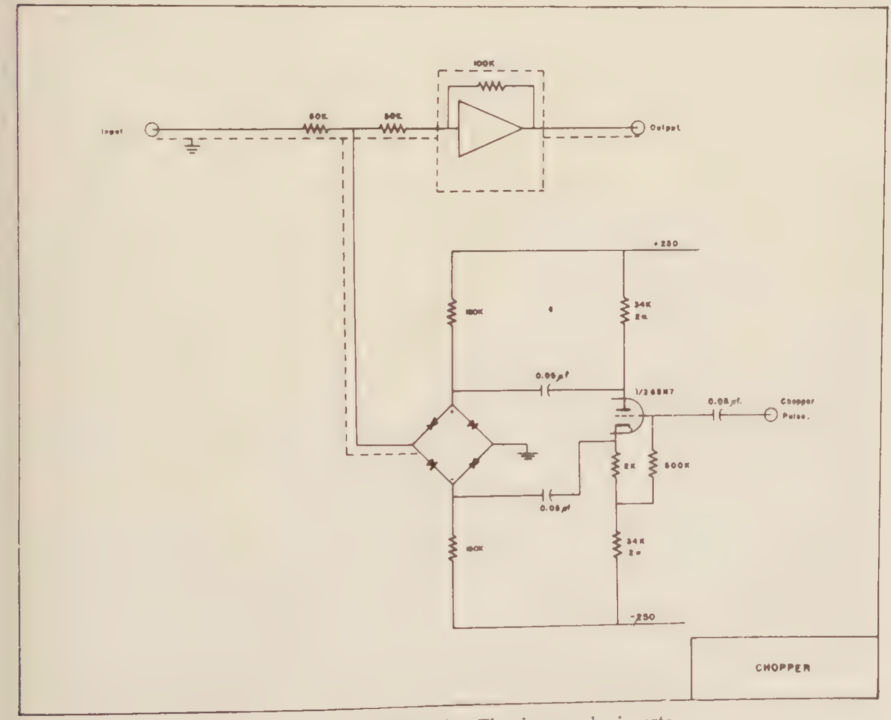


FIGURE 3. Chopping circuit. The chopper also inverts.

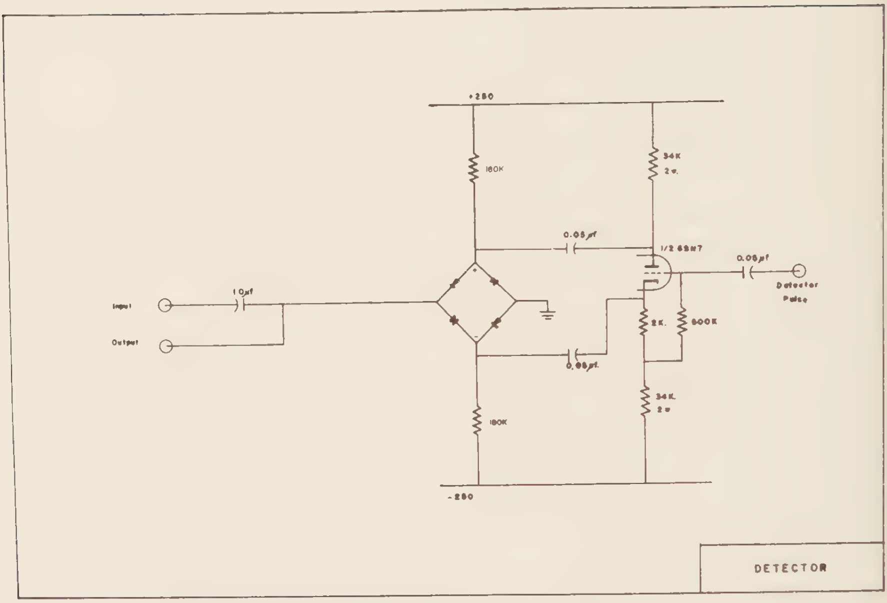


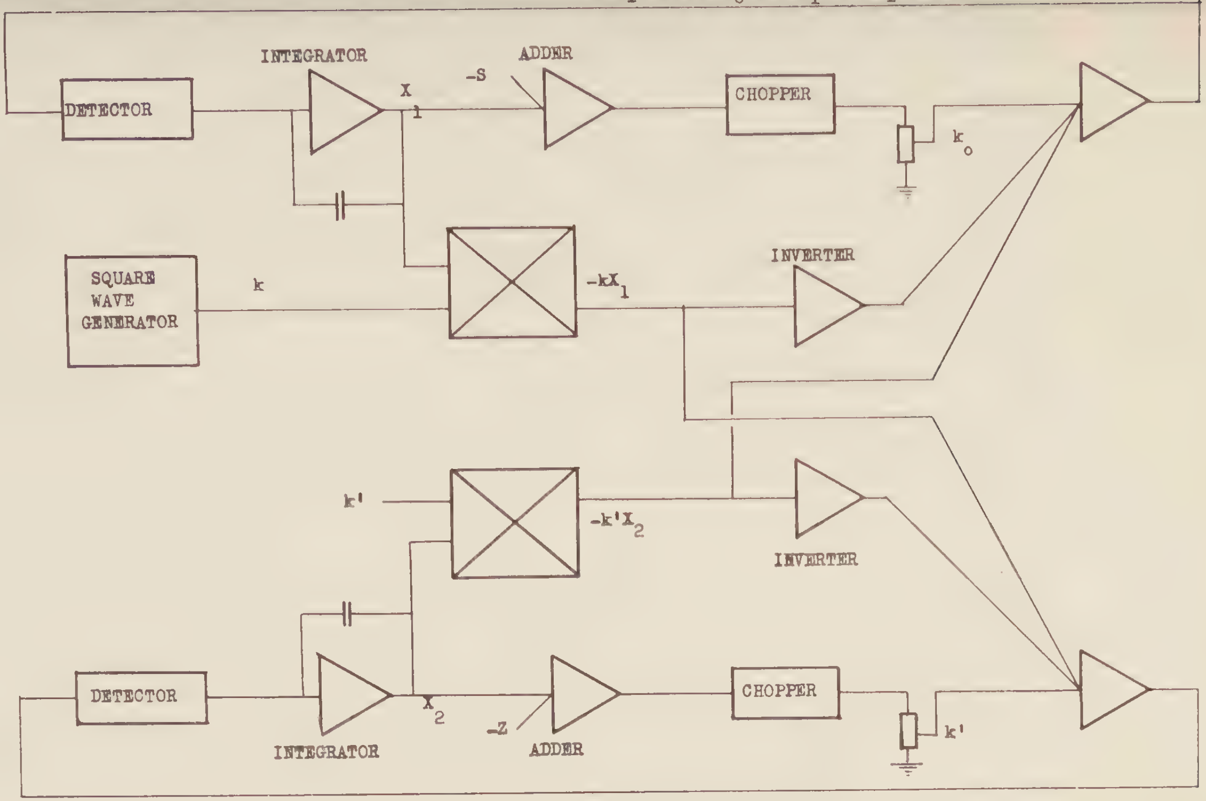
FIGURE 4. Detecting circuit. Due to the fact that the detecting pulses are 180° out of phase from those chopping pulses, the detector inverts.

synchronizing pulses for the computing cycle and also chopping and detecting pulses for the D.C. to A.C. conversion. Also, step voltages and time marks are generated for calibrating the display-oscilloscope.

Examples of Applications

In the study of the dynamical behavior of an enzyme system, a differential equation describing the transient formation and disappearance of intermediate compounds can be written for the reactions that follow the law of mass action. Due to the fact that these nonlinear equations have no simple analytic solutions, synthesis of any mechanism from experimental data is a cut-and-tried procedure for which a large number of numerical solutions are required. An example of the way in which the computer was used in a study of the mechanism of the action of catalase has been given in great detail.[3] In this reference, choice of proper scale factors relating the equations solved by the computer to those given in chemical terms has also been described.

A more interesting example is the study of the behavior of an open system subjected to a change of environment; that is, when the intensity of some "stimulus" to which the system is sensitive is changed to a new level, the "transient response" of each of certain variables of the system shows a characteristic "overshoot." This characteristic has been treated by Burton[4] both analytically, by actually solving the equations, and analogously, by setting up a water-flow system. The same problem is used here to demonstrate



$$dX_2/dt = k_2(Z - X_2) - k'X_2 + k X_1$$

FIGURE 5. Block diagram of the analog computer connections for the simple open system. The multiplier gives an A.C. output voltage out of phase from that of a chopped positive voltage. Thus a negative sign is added.

the use of our computer. A simple open system is shown as

$$S \overset{k_o}{\longleftrightarrow} \underset{X_1}{A} \underset{k'}{\overset{k}{\longleftrightarrow}} \underset{X_2}{B} \overset{k_2}{\longleftrightarrow} Z$$

where the source S and sink Z are maintained constant, k_0 and k_2 represent diffusion constants, k and k' are the forward and backward rate constants of the first order reaction, A and B are the reactants of concentrations X_1 and X_2. The problem is to find the transient behavior of the concentrations X_1 and X_2 when the system changes from one steady state to another by changing the rate constant k or k'. In the computer set-up, a square wave generator synchronized with the computing cycle is used to give a voltage corresponding to the rate constant. The computer set-up is shown in FIGURE 5. FIGURE 6 shows the square wave change k and the transient behavior of concentrations X_1 and X_2 as a typical solution. This picture shows also the transient forma-

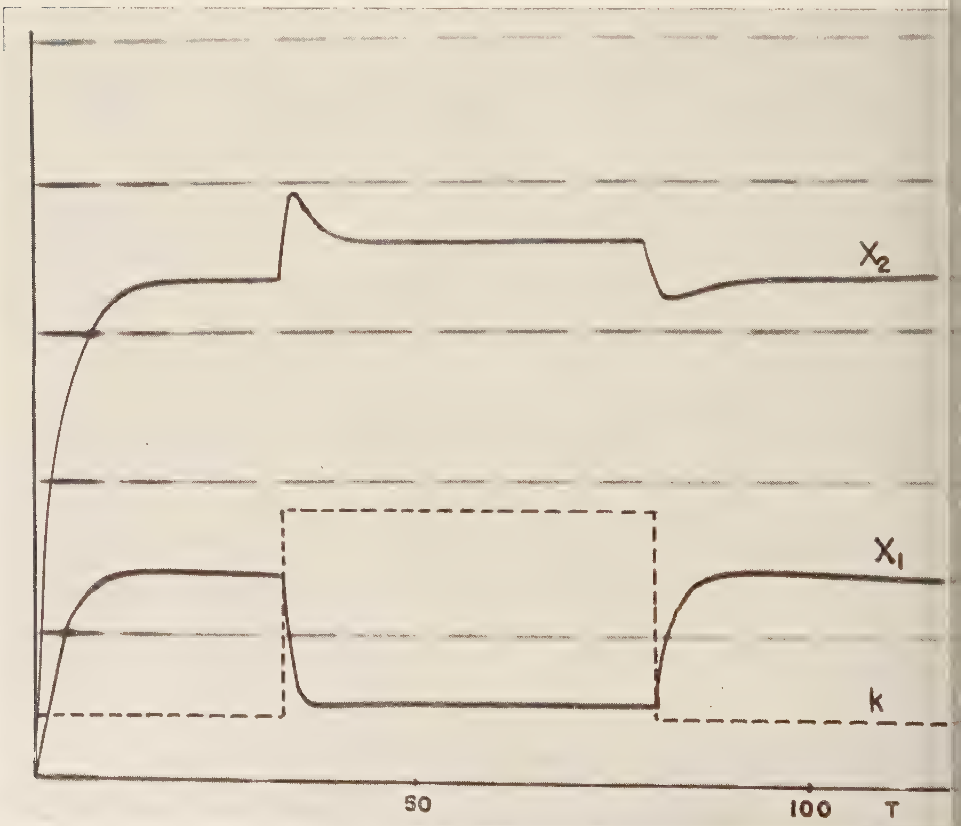


FIGURE 6. A typical solution for the case $S = 1.0$, $Z = 0.5$, $k_0 = 0.1$, $k_2 = 0.4$, k changes from 0.24 to 0.8, $k' =$ Time scale is in seconds. Concentration scale is arbitrary because concentrations are linearly related in this particular

tion of X_1 and X_2 from time zero to the first steady state. In case this initial formation is slow, we can set the steady state values of X_1 and X_2 as the initial values of the corresponding integrators. Then the system will be in the first steady state at the beginning of the computing cycle.

Acknowledgment

The computer has been developed under the direction of Doctor Britton Chance. John Busser and Matthew Conrad participated in the initial phase of design and construction. Joseph Higgins had worked with the writer in the latter phase of development and in application to actual problems.

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ELECTRIC ANALOG COMPUTERS: CLASSIFICATION, DESIGN, AND APPLICATION

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Introduction

The field of large-scale computing devices has grown so rapidly that some confusion exists regarding nomenclature. In part, this confusion can be explained historically from different concepts and developments. In part, it is due to a cross-fertilization of fields and to the development of "hybrid" types of computers. The term "analog computer," particularly, is used for two rather different types of device, and it has been suggested that it might prove desirable to distinguish between "active element analog computers" and "passive element analog computers."

Analog computers may be defined as devices which permit the study of a phenomenon in one field of physics (*e.g.*, heat) by carrying out experiments in a different field (*e.g.*, electricity). One characteristic distinguishing the two types of computers is the nature of their components. This distinction can be understood by using resistors as an example. Take the case where a resistor is needed, with its value changing with potential. In case of a passive element computer, a resistor which changes resistivity with voltage is used. Lacking such a resistor, changes are made in discrete steps. In active element computers, an electronic circuit is devised which behaves in a manner equivalent to such voltage-dependent resistance.

Active element analog computers comprise, then, adding, subtracting, multiplying, dividing, integrating, and differentiating elements. Such elements are combined into a circuit which is capable of solving many common differential equations. They can solve partial differential equations only by approximation, and this approximation frequently requires laborious work.

In the case of passive element analog computers, the analogy between the field of endeavor (*e.g.*, heat flow) and that of experimentation (*e.g.*, electricity) is generally much closer. Almost without exception, one can describe each single circuit element as representing, and representing directly, a part of the physical system which is to be analyzed. In view of this rather strict analogy, one can argue that only passive element computers are true analog computers, although frequently the active element computers are also referred to as "analog computers." Thus, in further discussion, the term "analog computer" will always be understood to mean those of the passive element type.

I. CLASSIFICATION

The concept of analogy computation is so fruitful that a large number of methods and devices have been developed on that basis. The various methods can be classified by the "analogous field" in which the measurements are carried out: electrical, hydraulic, optical, soapfilm analogs, *etc.*

This paper deals only with electric analog computers, which can be grouped in some specific classes. These distinctions may become clearer by introducing an example. Say that the temperature rise in a slab initially at constant temperature should be computed, if one surface is raised suddenly to a new temperature. This problem is one of transient nature, temperatures changing with time. It is described by the equation

$$\frac{\partial t}{\partial \tau} = \alpha \frac{\partial^2 t}{\partial x^2} \tag{1}$$

the notations being t = temperature, τ = time, x = distance from "hot" surface, α = thermal diffusivity. Now, the voltage rise in a noninductive cable, one end of which suddenly experiences an increase of voltage, is expressed by EQUATION 2:

$$\frac{\partial v}{\partial \tau} = \frac{1}{c\rho} \frac{\partial^2 v}{\partial x^2} \tag{2}$$

the notations (in addition to those above) being v = voltage, c = capacity, ρ = resistivity. Obviously a solution to EQUATION 1 describing heat flow can be had by solving the analogous EQUATION 2, describing flow of electric current in a cable, provided that c and ρ are selected appropriately. The solution of EQUATION 2 could be found by measuring electrical units, provided such cable were available. It would then represent a geometric analog of the slab. However, it is practically impossible to find a cable with values of c and ρ suitable for experimentation. Therefore a lumped network technique is required, in which resistances and capacitances are used. This technique, again, has certain limitations and, accordingly, a third combined method is used. Therefore the following important distinction can be made between (1) geometric computers, (2) lumped network computers, (3) combined computers.

(1) *Geometric computers* consist of an electric conductor which is given the shape of the body under investigation, which may be called "model," either reproducing this body at full or at reduced scale.

Potentials, currents, resistances in the model correspond to those in the "body," as the object under investigation will be called hereafter.

If it were possible to devise a model which not only had the appropriate resistivity but also a coefficient of inductance and/or an appropriate dielectric constant, it would be possible to use such models also for processes in bodies which electrically correspond to inductance and/or capacitance.

However, no methods or materials have become known in which capacitance or inductance of the model have been used in addition to its resistance.

Where such requirements prevail, it has been customary to resort to lumped network computers.

(2) *Lumped network computers* result from the application of the "lumping technique," common in electrical engineering, to analogy work. The "body" is thought of as being divided into a number of sections or lumps. The properties are being considered concentrated regularly in the sections: along the body's axes; in the center; or at the surface.

Certain limitations, more fully described hereafter, make the third type attractive.

(3) *Combined computers*, as the name implies, combine certain features of the "geometric computers" with some of the "lumped network computers."

II. GEOMETRIC COMPUTERS

(1) *Principle*

Such computers consist of an electrically conducting medium, which is given the shape of the "body." Electric potentials are applied at "analogous points" and currents and/or potentials are measured. For this purpose, voltages and/or currents are applied to correspond with the boundary conditions, and voltages at other points are read by means of a movable probe, connected to an instrument for measuring potentials, the position of the probe being changed after the measurements. By its very nature, the "model" must be built separately for each investigation and must be limited to problems requiring only resistances (*e.g.*, in heat terms, to steady state problems).

(2) *Design*

A large variety of methods and materials have been used for this kind of investigation. Metal foil, metallized paper, absorbent (blotting) paper saturated with a conducting solution, and conducting liquids contained in tanks are the most frequently used conducting media.[1] With the exception of liquids, the above-mentioned media lend themselves only to the study of two-dimensional problems. The conductors need a smooth insulating base. Application of potentials can be accomplished by painting or otherwise depositing a better conducting material on the model, or by screwing or clamping the electrode on the model. Application of such electrodes need not be limited, of course, to the circumference. FIGURE 1 shows, schematically, application of circular electrodes in the center of a rectangular model. FIGURE 2 is an example of the way that the electrodes may be fastened.

Liquid resistors usually consist of an electrolytic solution. Accordingly, in order to avoid disassociation, they require use of alternating current, while the other models may use direct or alternating current. Containers for liquids must, of course, be nonconductors, and they must not be chemically attacked by the liquid. Glass satisfies these conditions, but it is objectionable if complex shapes have to be formed. Plaster of Paris, cement, and wood have been used, but they all call for a coating to make them impermeable for liquids and, at the same time, the coating must be chemically inactive.

Geometric computers are limited to study of isotropic materials. A further limitation, previously existing, has been overcome: it is now possible to represent bodies composed of two or more materials requiring, in the model, different resistivities (*e.g.*, thermal studies of composite bodies with different conductivities in different parts). In two-dimensional work, this end is either accomplished by joining two sheets of different resistivity or, according to Kayan,[2] by cutting out holes in a regular pattern from a sheet, thus locally increasing the

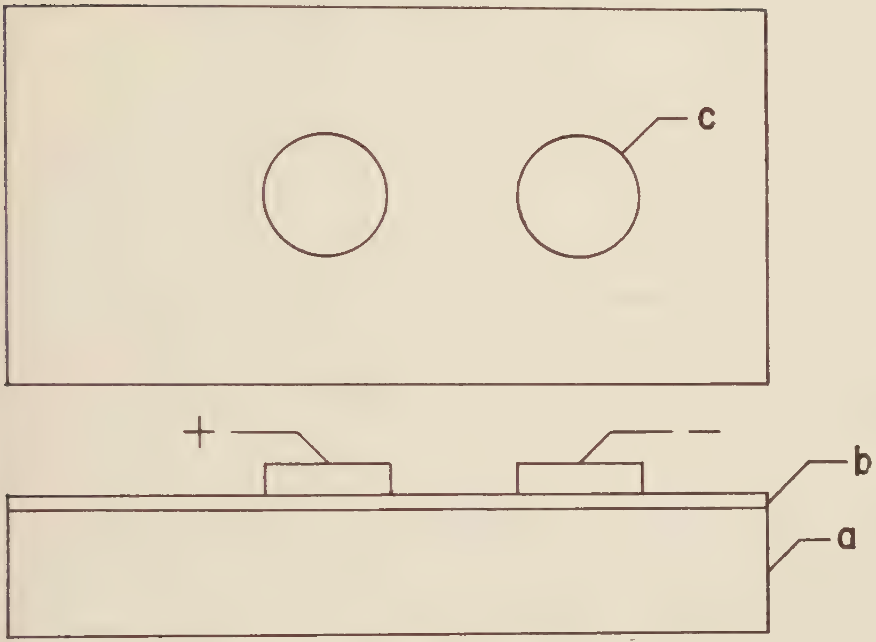

Figure 1. Round electrodes on rectangular sheet: *a*, insulating base; *b*, resistance layer; *c*, electrodes.

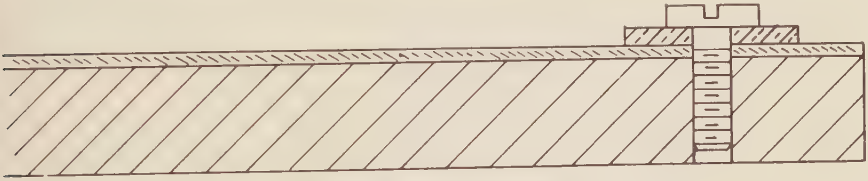

Figure 2. Connection of leads.

resistivity. This latter method overcomes the difficulty of joining the two sheets. In tanks, when used two-dimensionally, the change can be accomplished by varying the depth in accordance with resistivity. Figure 3 illustrates such a tank.

The scale factor, relating the body to the model, can be chosen arbitrarily, governed by availability of space, desired accuracy in location of measuring points, *etc.*

One of the earliest, if not the earliest, geometric computers, described by Langmuir[3] and his co-workers, was characteristic, in at least one respect, of many later designs, namely in the assumption of an isopotential boundary. Such an assumption, however, is unwarranted in many instances. Take, for example, the case of a heat-flow problem in which the boundary condition is given in form of an unknown ambient temperature and a boundary conductance (sometimes described as "surface coefficient," "film coefficient," *etc.*). In case of unidirectional flow (which of course does not require a computer) such bound-

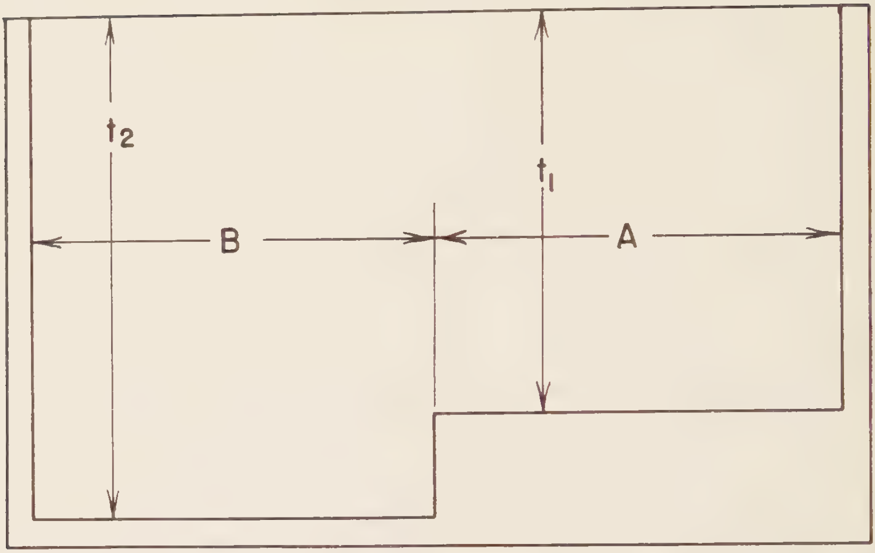

FIGURE 3. Tank with uneven depth. Zone *A* represents material with a conductivity smaller than that of zone *B* by a ratio t_1/t_2.

ary conductance (*h* Btu/sq.ft.hr.F.) can be treated as an extension of the wall (conductivity *k* Btu/ft.hr.F.) by a distance *k/h*. But in two-dimensional work, as represented by a corner (FIGURE 4), such procedure is not permissible, because in the wall "extension," representing the boundary conductance, there is, but should not be, a finite resistance parallel to the surface.

Therefore application of discrete resistors (FIGURE 5) has been suggested, which connect to individual points on the surface. Strictly speaking, this arrangement represents, however, a computer of the "combined type" (see section IV), because the "boundary conductances" are lumped.

One of the most frequent problems in connection with such computers consists of mapping the potential field. Mapping can be done conveniently by comparing each individual voltage with the main voltage; *e.g.*, that applied to the boundaries. A number of circuits have been devised to facilitate these readings and, in addition, geometric arrangements to locate easily the position of the probe during such mapping operation have been developed.

(3) *Sources of Error*

Most investigators using this kind of computer have been satisfied to state one or more sources of error without analyzing their magnitude or influence on results.

(a) One of the most obvious sources is nonuniformity of the resistance material. Such nonuniformity exists in geographic distribution (*e.g.*, areas of greater and smaller thickness), as well as in the form of anistropy—resistance in one direction of a coordinate system being consistently larger than that in the other direction. This error becomes significant as the size of the

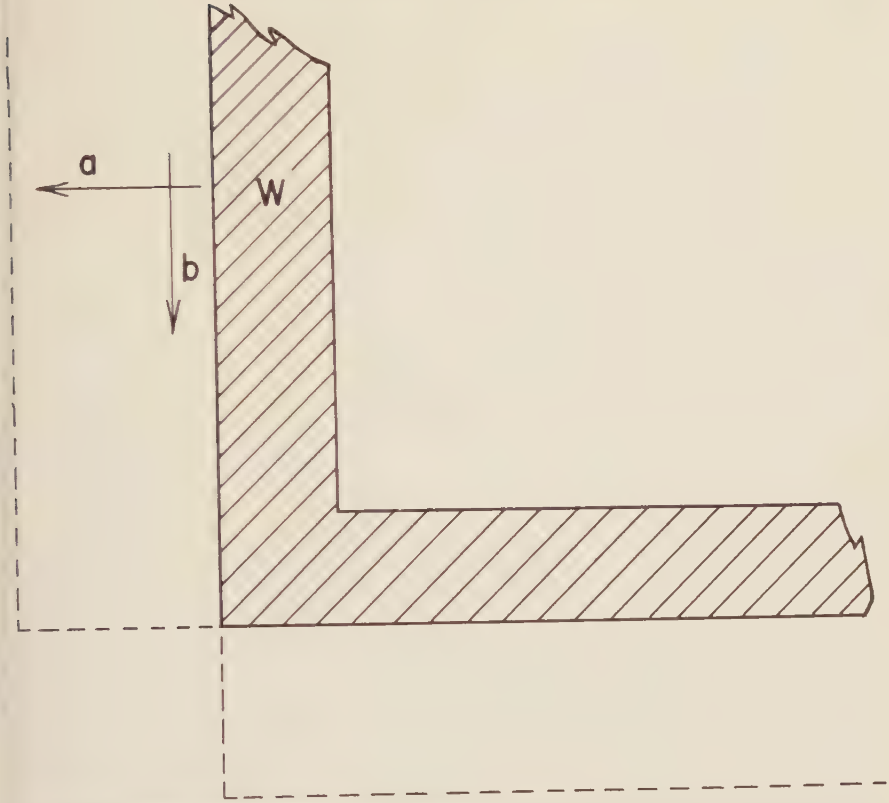

FIGURE 4. Corner of furnace wall: *W*, wall; conduction in direction a, boundary conductance, but conduction in direction b has no thermal equivalent.

model increases, because it is easier to select a relatively uniform area within a small piece of material than in a larger one. Beyond care in selection, probably nothing can be done to counteract random unevenness. In case of anistropy of the model material, it has been suggested that two models be used, arranged so that any given direction in the body is first placed in one direction in the model, and then in a direction 90 degrees different. The results are to be the averages of these readings obtained with the two models. No analysis of the improvement achieved by this technique, nor the error inherent in a given nonuniformity of the model material is given.

(b) A second source of error lies in locating the probe. The probe, connected to the potential measuring device, is inserted at different points in the model. In order to plot the isopotential lines, the exact location must be known. Since the space measurements can be carried out only with a finite degree of accuracy, the percentage error decreases with increasing size of the model.

(c) A further source of errors is caused by leakage. The insulating base on which the conducting material rests or the tank containing the liquid resistor

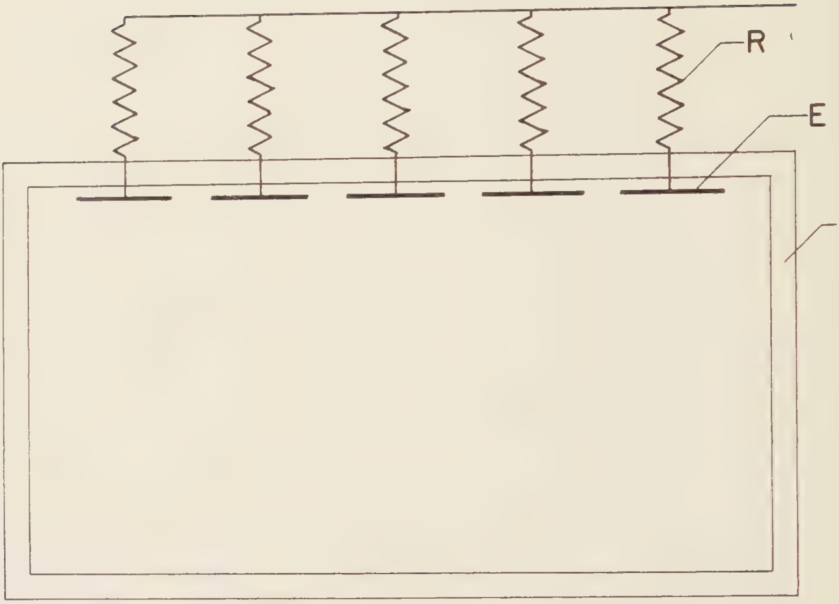

Figure 5. Tank with discrete resistors: *T*, tank; *E*, electrodes; *R*, discrete boundary resistors.

form a shunt to the useful resistance. Such a shunt, of course, falsifies the results. This error becomes significant only when the useful resistance is high. This resistance, in turn, is usually high only in case of liquid resistors.

(d) Finally, a systematic error is inherent in the introduction of boundary conductance. Reference is made to figure 5. The contact connecting the discrete external resistor to the continuous medium has an optimum size, not yet explored. If the contact becomes too small, the interval becomes too large and the flow lines crowd in an unrepresentative manner. If the contacts become large, there is a tendency to form a short circuit between adjacent contacts.

III. LUMPED NETWORK COMPUTERS

(1) *Principle*

"Lumping" of an electric circuit is a commonly accepted procedure in electrical engineering. A body with evenly distributed properties is thought of as replaced by one subdivided into sections or lumps, the properties being concentrated in the center or on the axis of the limps. Thus an electric network is created, representing the "model" (see section II) which, in turn, represents the body.

In case of transient problems, the network takes a position mathematically between the analytical solution and the finite difference solution. With the latter, the network shares the geometric lumps, while the time variable changes continuously in case of the analog computer, but in finite steps in the finite difference method. On analog computers for transient experiments, the computing experiment is not necessarily carried out in the same length of time as the actual occurrence. A time scale may be applied, stretching the computing time in case of rapid occurrences and condensing the time in case of study of very slow processes.

(2) *Design*

A computer of this type consists essentially of a large number of "passive elements," resistors, capacitors (and, for the simulation of certain kinds of equations, inductances). Pure resistance networks are used for the solution of Laplace's equation and can be characterized by the number of nodes and the number of directions (two- or three-dimensional; n nodes).

Resistance capacitance networks operated with D.C., which are described hereafter, can be grouped according to the length of the computing experiments: short-time computers complete the "computing experiment" in fractions of a second; medium-time computers, in a few seconds; and long-time computers, in several minutes. The equipment which will be briefly described here is a "long-time" computer, consisting of a resistance-capacitance network, suitable for the solution of heat conduction problems with constant or variable parameters, for diffusion problems, and for certain kinds of stress problems. Length of computing experiment is usually from 5 to 15 minutes.

The Heat and Mass Flow Analyzer[4] consists essentially of resistors, capacitors, power supplies, instruments, relays, and the necessary means for connecting these elements into an arbitrary circuit arrangement with minimum effort. FIGURE 6 shows, schematically, the layout of the equipment, which crowds a 21- × 28-ft. room.

The large resistance frame R_1 comprises a two-dimensional network of 576 nodes (1152 resistors). In FIGURE 7, the diagram for one node is shown. Each resistor consists of three pairs of clips, in which units of appropriate values can be inserted. Thus, each resistor can be set to three digits. Provision has also been made at each node to feed in and drain currents. The necessary resistors can be set to two digits. The ends of each horizontal and each vertical resistor are connected to outlets, each outlet ("jack") receiving one end each of two resistors. One node consists thus of two outlets, which normally are connected, but can be separated by means of a knife switch, S. When all these knife switches are open, the network resolves into a number of separate unconnected rows of resistors (horizontal and vertical). The outlets serve to insert meters, power supplies, or capacitances at each node.

Each of the two smaller resistance frames R_2 comprises sixty resistance sections, with resistance values adjustable in 100 ohm steps from 100 ohms to 1.11×10^6 ohms. Provision is made to obtain lower as well as higher values, if required.

Each of the three capacitance frames (C) consists of four rows of nine trays, each tray carrying a number of capacitors. Adjacent to each vertical row of trays is a busboard with 12 busses, each bus having a number of outlets. One pole of each capacitor is grounded permanently, while the other is brought out

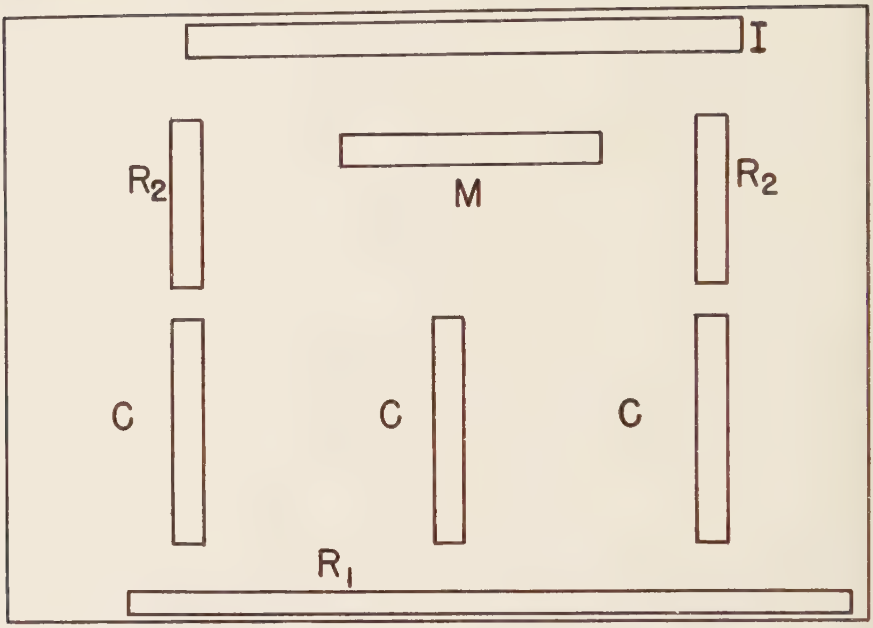

FIGURE 6. General layout of heat and mass flow analyzer: R_1, R_2, resistance frame; *C*, capacitor frame; *M*, main panel; *I*, instrument panel.

to a double outlet. Capacitances are set up by inserting jumpers from the jacks on the trays to the busses. A total of 3000 microfarad is available.

The "main panel" *M* has several boards: one has double outlets, one each for each end of every resistor section on R_2. These double outlets are so arranged that, by means of a multiple plug, one end of each of four resistors can be connected to form a node similar to that shown in FIGURE 7 for board R_1. The multiple plug also provides a "jack" (outlet) for connection of instruments and capacitances. Two boards on panel *M* receive the ends of all busses from the condenser frames, and two more boards provide for easy clearing of the board for new experiments.

The instrument panel comprises isolating amplifiers, voltage and current recorders, a current-time integrater, and batteries as power supplies.

A number of specialized devices, such as an occurrence-time recorder, an input program device, and constant current sources are available. Relays serve to change resistances and capacitances when representing a nonlinear system.

(3) *Sources of Error*

(a) *Components-resistors and capacitors.* These devices are accurate to within plus/minus 1 per cent. If greater accuracy is required, units can be calibrated. Even with 1 per cent error, however, the probably error in the results is much smaller, since over- and under-size units occur in a random man-

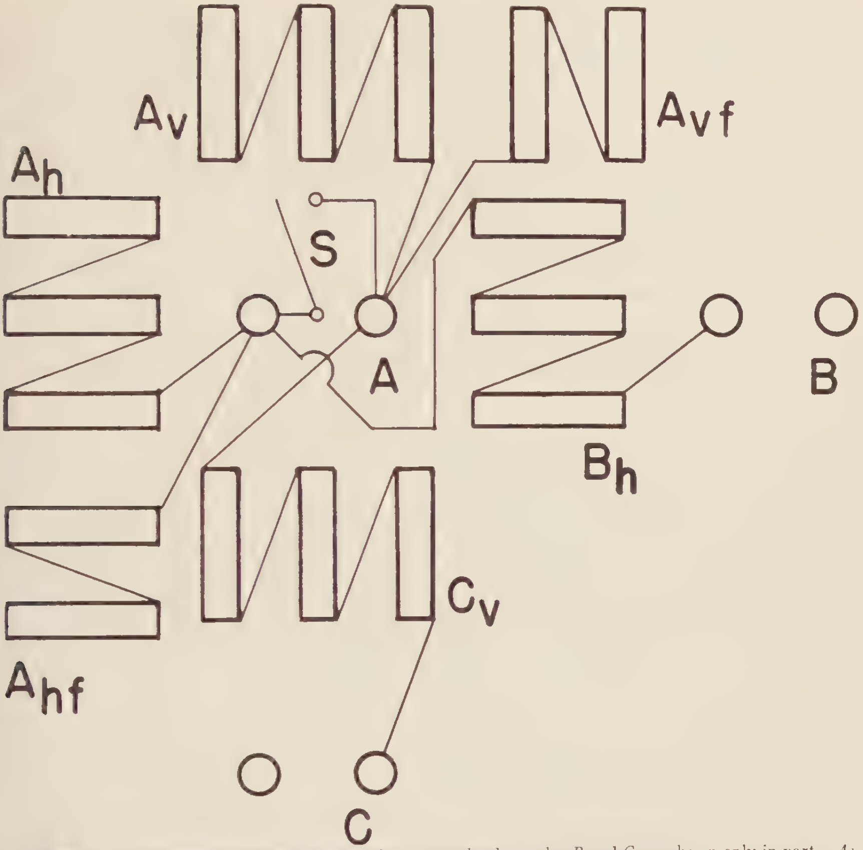

FIGURE 7. Arrangement of node. Node *A* shown completely; nodes *B* and *C* are shown only in part. A_h, horizontal resistor, node A; A_v, vertical resistor, node *A*; B_h, horizontal resistor, node B, B_v, vertical resistor node C; A_{hf} and A_{vf}, feed-in and drain resistors, node A; *S*, switch.

ner. Too-high values in one section are frequently compensated by too-low values in adjacent sections.

(b) *Leakage.* There is no pure capacitance. In each unit there is inevitably leakage between the terminals. This leakage, measured by the time constant of the capacitor is of the order of magnitude of 12 to 30 hours. In addition to the condenser leakage, however, leakage occurs from the busses, in the isolating amplifiers, *etc.* To minimize the effect of leakage, utmost care is taken in designing insulation. Surface leakage is reduced by providing an air-conditioned room, keeping the relative humidity at approximately 40 per cent. In problems involving *R-C* networks, it is usually possible to select capacity and resistivity in an arbitrary manner, using for a given time scale high capacity and low resistivity or vice versa. From the viewpoint of leakage, it is desirable to select capacitances as high as possible.

(c) *Instrument errors.* The electric measuring instruments have an accuracy of $\frac{1}{3}$ of 1 per cent of full scale. All instruments are multiscale (in case of voltage measurements, scale selection is built into the isolating amplifiers), and thus advantageous parts of the scale can be used. Amplifiers are extremely linear, and zero drift is limited to about 2.5 mv. after warming up.

(d) *Lumping errors.* The use of a finite number of lumps entails errors, the magnitude of which changes (1) with time, early times having a greater error; (2) with location, points near the boundary or surface generally showing greater errors; and (3) with the nature of the problem.

Fortunately, the percentage error decreases very rapidly with increasing number of sections: the improvement by increasing the number from one to two sections is larger than that obtained by providing three instead of two, *etc.*

Systematic studies of such errors have been published only for the simple case of a one-dimensional homogeneous network for simple boundary conditions.[5]

Where error considerations are important and theoretical analysis is impossible or impractical, one can solve the same problem two or more times, using in the different solutions varying degrees of coarseness of the network. The finer network with more lumps gives a more correct answer and, from the convergence of the results, one can estimate the deviation from the correct result that would be obtained with an infinite number of lumps.

Where available equipment is insufficient to get results of desired accuracy, time and effort can sometimes be used to substitute for lacking material. For example, all available nodes can be used to study early times near the surface. Then, in a second run, with different lumping, the occurrences can be investigated in regions which are far removed from the surface and which, during the early times, were not affected at all.

(e) *Relative errors.* Usually only relative errors are of interest, not absolute errors. In defining such relative errors, the point of reference is of importance. In instruments, for example, it is customary to define the error in percentage of the full-scale value of the instrument. At the lower parts of the scale the relative error is considerably higher. But frequently that is acceptable, because the reference to full scale is the significant comparison. Similar considerations must be made in computations. Take, for example, a potential time curve (FIGURE 8). A slight deviation in the early parts of the curve, hardly readable on the graph, may be as high as 10 per cent or more, when compared with the theoretically correct value prevailing at that time.

If this error is considered excessive, then the procedure mentioned in (d) should be used, carrying out a computing experiment, limited, say, to the time interval *A*, FIGURE 8. Thus potentials during this period can be measured accurately.

IV. COMBINED COMPUTERS

Geometric computers are less restricted as regards shape. Lumped network computers are more flexible as regards boundary conditions and components (capacitances and inductances can be used). Thus, it is obvious that attempts should be made to combine the advantages of both types of computers.

Three types of such combinations are mentioned here:

(1) Applying boundary resistances has been mentioned above (section II, 1), and it is shown in FIGURE 5. As the number of sections increases, the resistance of each of the units r increases, and this sets a practical upper limit to the number of resistors applied.

(2) When selecting the time scale (see section III, 1) equal to unity, a "true time computer" results. In such case, one can combine parts of the process apparatus with part of a computer; *e.g.*, one may study a temperature control device by connecting the control device to an analog computer, the latter representing the process.

(3) For the study of transient conditions in complex shapes, one may use a geometric representation of the resistance pattern and insert electrodes leading to discrete capacitances and resistances. Such a method is in development at present.

V. APPLICATIONS

The field of applications is almost unlimited, and therefore no attempt will be made to give a complete listing. Also, the use of analog computers has so spread that it is no longer practical to list the applications through an exhaustive bibliography. A list of publications of the Heat and Mass Flow Analyzer Laboratory, complete to the date of publication, is contained in a report in *Metal Progress*.[6] But, since the appearance of the list in 1947, a number of

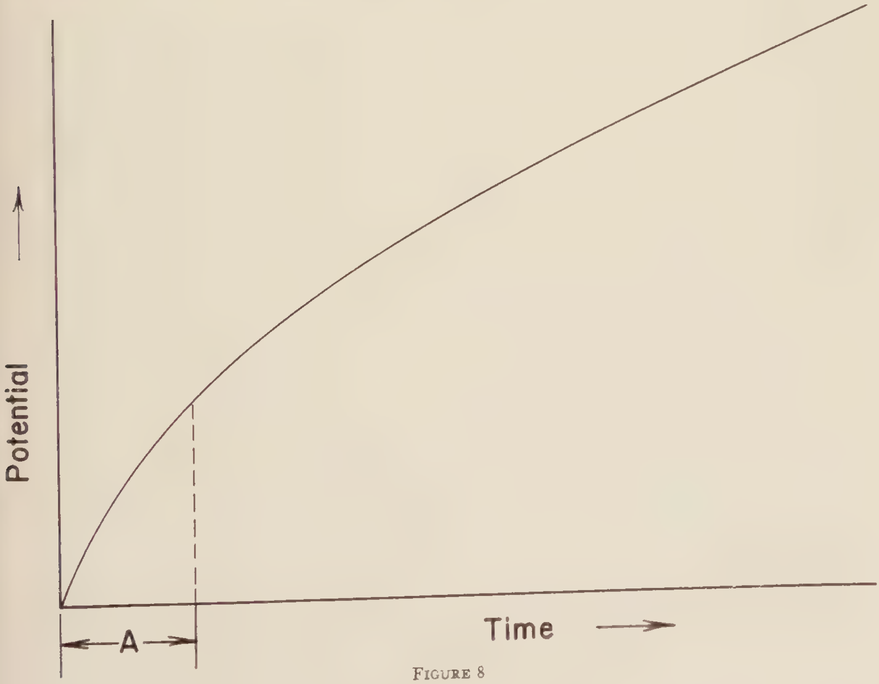

FIGURE 8

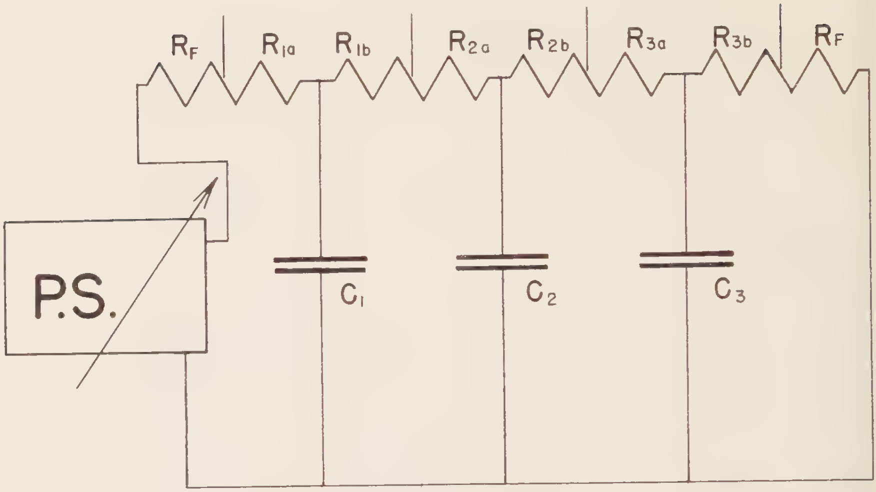

FIGURE 9. One dimensional circuit.

papers have appeared. Reference should also be made to the compilation by Mindlin and Salvadori[7] regarding such computers in the field of stress analysis.

Instead of giving an incomplete list of applications, or even of fields of applications, a few examples are discussed in greater detail. For reasons of personal interest, the problems selected are in the field of heat flow.

(1) *Wall.* A wall of sufficient size to make end effects negligible is facing, on either side, and ambient (an extension of the example mentioned in section I). The temperature of one ambient is constant, while the other changes. Such a wall can be represented by a simple *R-C* network, FIGURE 9. The potential of the constant ambient is used as reference, and the potential of the power supply, *PS*, is adjusted proportionally to the difference of potentials of the two ambients. The capacitances C_1-C_3 are inserted at the center of the resistance sections r_{1a}, r_{1b}; r_{2a}, r_{2b}; and r_{3a}, r_{3b}, respectively. Boundary resistances (the inverse of boundary conductances) are represented by resistors R_F.

The circuit is computed based on the following system of analogies:

Thermal System	Electric System
Conductivity	1/Resistivity
Volumetric specific heat	Capacity
Temperature	Voltage
Rate of heat flow	Current

If the two ambients are at the same temperature, the process is one of heating up to a constant temperature. In such case of symmetry, no heat flow can occur across the center plane, and it is sufficient to represent, on the computer, one half of the wall.

Using cylindrical or spherical coordinates, problems involving solid or hollow cyclinders or spheres are treated as one-dimensional problems.

(2) *Casting.* A long hollow cyclinder serves as mold to freeze a liquid poured into it; consider the system long enough to disregard end effects; let the filling

take place in so short a time that practically no cooling takes place until the mold is filled. As the liquid cools, it contracts and shrinks away from the wall of the mold. The process may be represented by four circuits, connected as shown schematically in FIGURE 10.

L is the circuit representing the freezing material, M that representing the mold. G is the circuit representing the thermal resistance of the gap, and R that representing the cooling from the surface of the mold to the ambient.

Initially, L is charged to a voltage corresponding to the pouring temperature; G is initially bypassed by switch S, which is opened only when the gap forms.

Thermal conductivity and specific heat of materials change, usually, during solidification; moreover the change of state is accompanied by the release of the heat of fusion. In order to account for these nonlinearities, circuit L must be designed in a special way. FIGURE 11 shows one section of such circuit, the several sections being composed similar to those of FIGURE 9. Here the case is shown that only one value of liquid and one of solid conductivity need be considered. If within the solid and/or liquid state, properties change markedly, the circuit can be enlarged accordingly. Usually, the conductivity of the liquid is lower than that of the solid. Resistors R_1 and R_4 are equal and represent the "solid conduction." By opening simultaneously switches a and b, resistors R_2 and R_3 are inserted. Resistor $R_1 + R_2$ and $R_3 + R_4$ represent the "liquid conduction." Capacitor C_2 represents the "solid specific heat," C_1 the

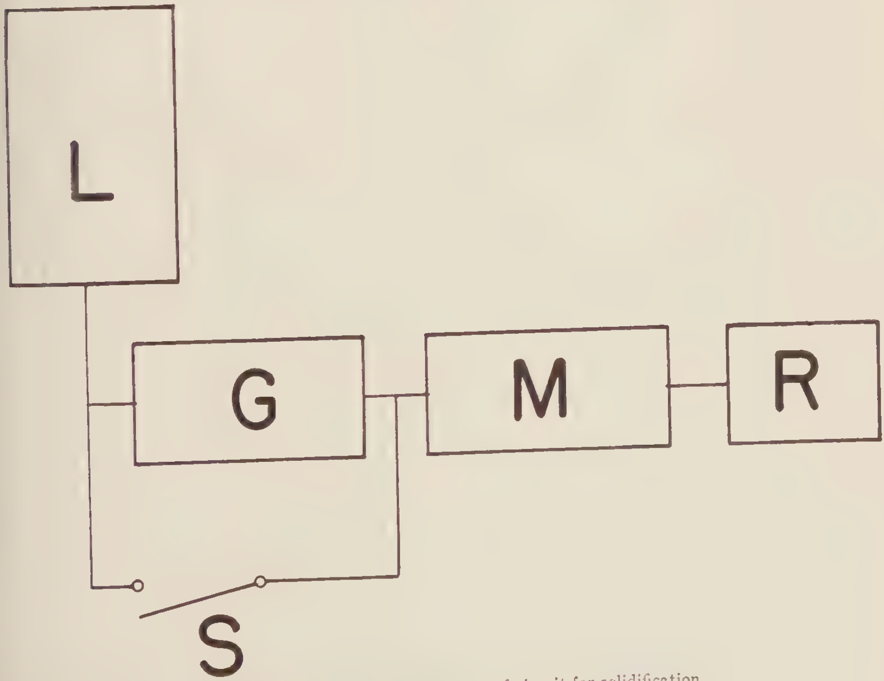

FIGURE 10. Schematic arrangement of circuit for solidification.

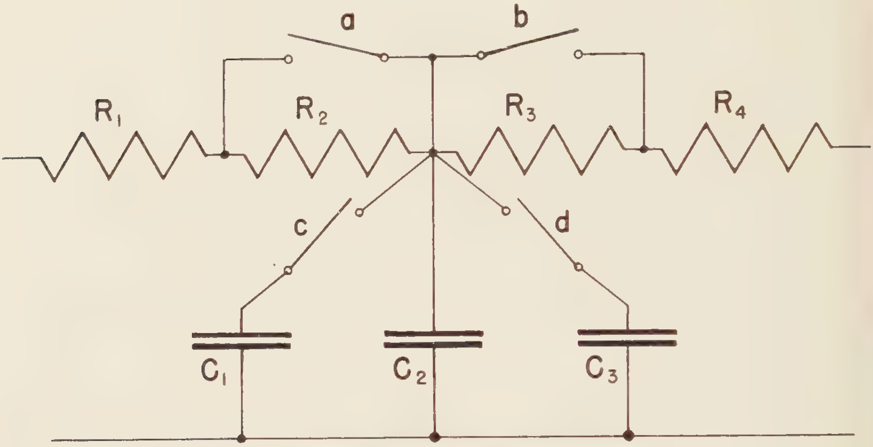

FIGURE 11. Node for solidification experiments (alloy).

difference between solid and liquid; finally, C_3 the heat of fusion (assumed to be liberated over a temperature range, as in case of an alloy), interpreted as temporary increase of specific heat.

Operation is as follows. Upon start of solidification (time zero) switches *a*, *b*, and *d* are open, *c* closed. When the liquidus point is reached, *d* is closed, connecting capacitance c_3 into the circuit. This capacitance is precharged to a potential corresponding to the liquidus temperature. Through the increased capacitance, the rate of temperature drop of the section is reduced. When the mean temperature between liquidus and solidus is reached, properties are assumed to change from liquid to solid values. This change is carried out by closing switches *a* and *b* and opening *c*. Finally, when the solidus is reached, switch *d* is opened, and the "heat of fusion capacitance" is taken out of the circuit.

If a material solidifies which has a definite freezing point rather than a range, no "heat of fusion capacitance" is used. Instead, a circuit as shown in FIGURE 12 is used. Here, the change of resistors and capacitance is not shown, since it is the same as in FIGURE 11. When the node has reached the freezing point, power supply *PS* is inserted, by closing the switch. *PS* is held at the "freezing potential." The current flowing from *PS* into the node is measured and integrated by *CI*. When as many coulombs have entered the circuit as correspond to the heat of fusion, the switch is opened.

In both cases shown in FIGURES 11 and 12, the entire circuit *L* may be one- or two-dimensional.

The circuit *G* consists of a single variable resistor, so computed as to represent radiation across the gap and conduction through the gas filling the gap, the gap being formed by the shrinkage of the casting.

The circuits *M* and *R* can be treated jointly: they are essentially the same as that shown in FIGURE 9, possibly two-dimensional.

(3) *Plastic.* Consider here the case of injection-molding toothbrush handles. A split mold is used, the cavity of which is filled with plastic. After the latter

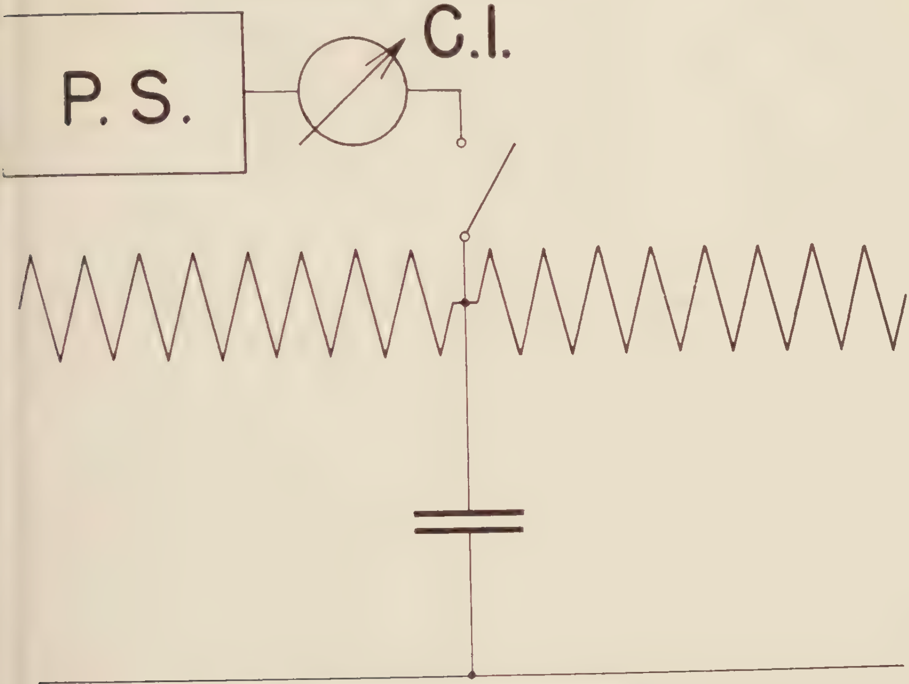

Figure 12. Node for solidification experiments (pure metal).

is set, the mold is opened, the newly formed handle ejected, and the mold closed again and filled for the next handle. Again, the circuit will be shown only in forms of a block diagram.

The problem involves a cycling operation, as far as the mold is concerned, but a transient temperature increase of the object (toothbrush handle) is considered. A computing circuit to handle this kind of problem consists essentially of four parts: (A) the circuit representing the mold; (B)(C) two identical circuits representing two handles (the reason for using two, and only two, circuits will become obvious from the description); and (D) the circuit representing the cooling of the mold surface after ejection of the handle.

In FIGURE 13, the four circuits are indicated by boxes, marked *A*, *B*, *C*, and *D*, and a box *S* represents a power supply to charge circuits *B* and *C* to the voltage corresponding to the temperature of the plastic entering the mold. The three circles I, II, and III represent three gangs of a switch, the common of each gang being connected to the corresponding circuits. Each switch has four positions, connected as shown. The wipers connected to the commons are shown in the "northwest direction," between two positions. The three wipers are moved simultaneously in a regularly intermittent rhythm.

In the first position (North) the mold and one plastic circuit (*C*) are connected; the plastic cools in the mold, while the other (*B*) is "preheated" (represented by circuit *B* being connected to the power supply). In the next position

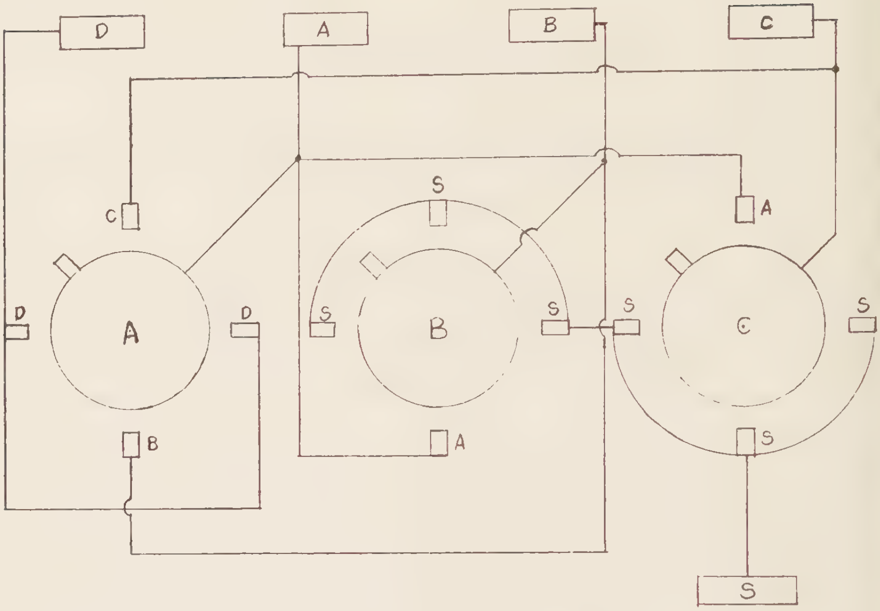

FIGURE 13. Circuit for curing of plastics.

(East), the mold cools while both plastic circuits preheat; then circuit *C* discharges (plastic *C* cools), *etc.* If the interval between shots does not equal the dwell time, the rhythm of the switch is regulated accordingly. Circuits *A*, *B*, and *C* are essentially of the same kind as that shown in FIGURE 9 while circuit *D* is a resistor (representing the boundary of film resistance), connected to the ground potential, representing the air in the shop.

(4) *Heat exchangers.* Tubular heat exchangers have been studied[9] by means of such a computer. In the simplest case of a parallel-flow tubular exchanger, the circuit consists of just two capacitors and a resistor (FIGURE 14). Each capacitor is proportional to the product of mass rate of flow and specific heat, c_H for the high temperature material, c_L for the low temperature one. *R* corresponds to the heat exchange resistance (including boundary resistance on either side of the tube and the thermal resistance of the tube wall itself). The length of the tubular exchanger is represented by the length of time, counted from closing of the switch. C_H is precharged to a potential corresponding to the initial temperature difference of hot and cold fluid. Under the influence of the potential difference current flows from c_H to c_L, until (theoretically) after infinitely long time (infinite length of the tubular exchanger), the two condensers (fluids) have the same voltage (temperature).

(5) *Determination of properties.* One of the most serious limitations of analog computers (a limitation, incidentally, which they share with all computing techniques, be they automatic or analytical) is the lack of knowledge of thermal properties of the materials involved. The computer, however, can be used to determine unknown properties. This recourse seems always advan-

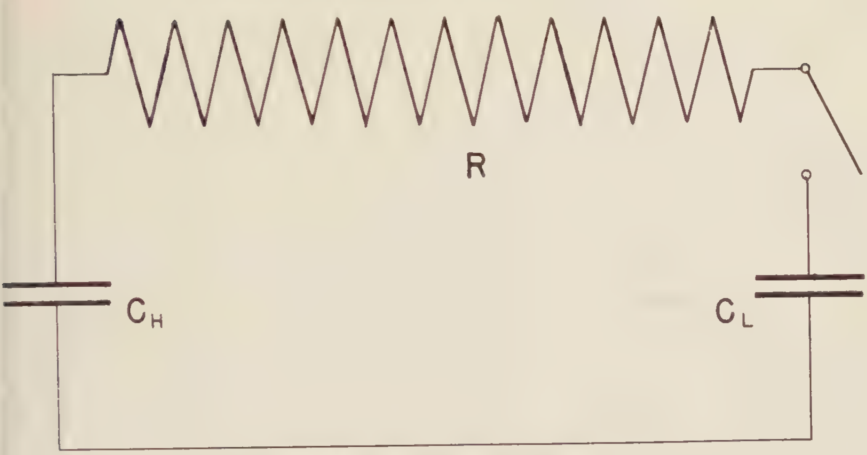

FIGURE 14. Parallel flow heat exchanger.

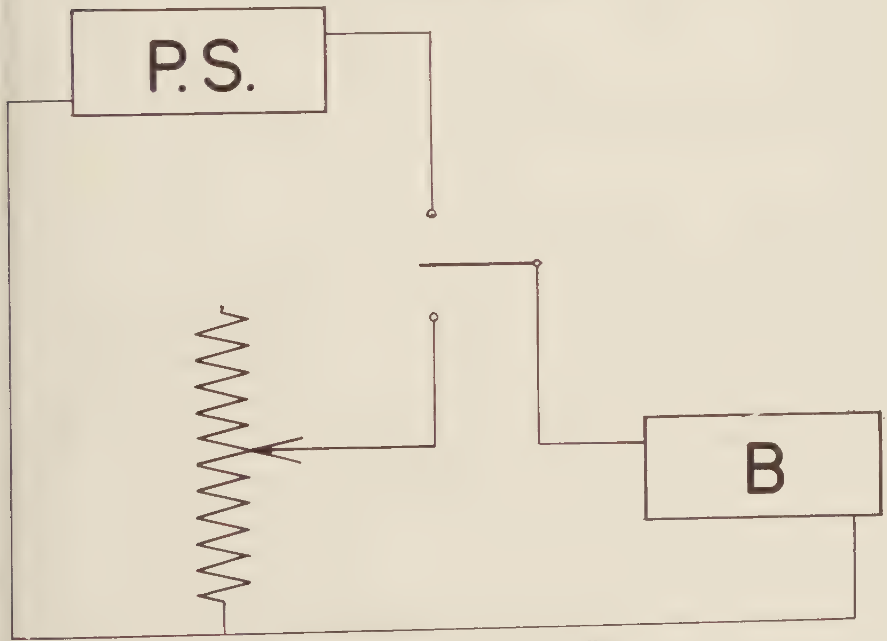

FIGURE 15. Circuit for quenching studies.

tageous if temperature measurements are easier than those required for obtaining the unknown quantity directly. An example will show what is meant. Determination of the boundary conductance is always a difficult procedure, but in the particular case where it is to be determined for a rapidly changing surface temperature, direct determination is almost impossible. Yet boundary conductance under such conditions is of great interest in connection with quenching of metals and glass. Because of the unique relationship between temperature within a piece and on its surface, one can carry out a quenching operation, measuring the temperature at a specified point in the body, and analyze the time temperature curve thus obtained on an analog computer. From the analysis, the boundary conductance as function of temperature is obtained. For the sake of analysis, a network similar to that shown in FIGURE 9 is built. Connections are as shown in FIGURE 15; here B denotes the network, not including boundary resistance, PS a power supply, and R_F the boundary resistance, which is presumably changing with surface temperature. While B can be built based on a knowledge of the properties of the body, the value of R_F is not known originally. B is precharged from PS, according to the initial temperature of the piece which is quenched. Then the switch is thrown to R_F, which is set to an arbitrary value. The start of the voltage time curve is taken at that point in the circuit which corresponds to the point in the body where the time temperature curve was taken. The curves will not match, and the test is started repeatedly each time with the value of R_F adjusted. Finally, the start of the two curves will coincide and the value of R_F at which this was achieved is noted. Then the same procedure is used for the next time increment of the temperature time curve. Each value of R_F is inversely proportional to the correct h value applying to the time step in question. At the same time, surface temperatures can be obtained on the computer and correlated with the boundary conductance values.

VI. PROBLEMS OF PERSONNEL

A discussion of analog computers would be incomplete without reference to the personnel involved. Each analog computer may be understood as a multilingual being and, since its anatomy on the one side, and input and output on the other, are meaningful in different languages, it is obvious that analog computers achieve their greatest usefulness in the hands of a team. To understand this requirement, consider briefly the procedure of use of such computers.

(1) In a given branch of technology, for example of welding, or of machine design, or of science, say biology, a specific question arises.

(2) This question, say in the field of heat flow, is separated and brought into a specific form, amenable to analysis.

(3) This "form" is translated into the field of the computer (*e.g.*, electricity).

(4) Computation experiments are conducted.

(5) Results are translated into the terms required (*e.g.*, heat).

(6) Application of these results to the initial problem of inquiry (*e.g.*, welding, *etc.*) must be made.

The computer, an intricate tool, needs maintenance. Thus the following personnel is required: (a) technology experts (welding, glass, *etc.*); (b) "field" experts (heat, diffusion, *etc.*); (c) translators "field"-computer; (d) computer operators; (e) maintenance personnel; and (f) development personnel.

It is not practical, and not customary, to have technology experts for all branches (welding, heat treating, *etc.*) on the computer staff. If this procedure were attempted, there would be need for a tremendous variety of people, and yet they would not necessarily know all the problems in their branches.

But the laboratory must have the "field experts" for each field in which it wants to operate; *e.g.*, if an analog computer laboratory wants to work in the field of heat flow, diffusion, and stress analysis, it must have an expert in each of these fields. These experts must be so broadly experienced that they can understand the "application experts" and, with only a very sketchy introduction, help crystallize the question out of the over-all application problem. They must have enough vision to indicate, at least in general terms, the type of computing circuit used. In intricate cases, the field expert will need a supporting team of mathematician and electrical experts. This team may be considered as "staff level." The jobs (*c*), (*d*), and (*e*) above are on the operative level and, while the staff level is full of challenging professional problems, the jobs on the operative level are singularly repetitive and monotonous: and yet jobs (*c*) and (*d*) cannot be delegated to technicians. The operator must see the results as they develop and, if unexpected things happen, call on the staff level for help. Since well-designed equipment does not call for very much maintenance, the person (or persons) on jobs (*c*) and (*d*) must usually also do the maintenance.

Thus, on the staff level, people of vision (for opportunities of analogy), of willingness and ability to understand the thinking of the others on the team, (mathematics, electric, field, *e.g.*, heat) are required; but otherwise these jobs are "normal."

On the operating level, however, one needs people who, while capable of critical and independent observation, are satisfied to a large extent with repetitive work. This difficulty is one which analog computers share with all other large-scale computing devices. An answer has not yet been found, and it will be found only if the scientist or engineer responsible for such devices can transcend the field of science, because the problems on the "operating level" become deeply human.

This conclusion may be a fitting end for this report. Large-scale computing devices, with their automatic possibilities seem, in a way, to have reached an utmost limit in dehumanizing technology. Yet their very operation brings one back to an essential item, to the human problem. This fact may well serve as a reminder that technology should serve mankind; that mankind should not serve technology.

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TRANSDUCERS IN INSTRUMENTATION

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The progress of science depends largely upon ability to measure various quantities and phenomena. As the pace of scientific development has quickened, stronger emphasis has been placed on accurate, sensitive, and more rapid measuring techniques. Nondestructive testing is of paramount importance in many branches of science. Electronics as used in mensuration possesses many desirable characteristics such as extremely rapid response, high sensitivity, and accurate control. The desirability of applying electric instruments in nonelectrical areas is apparent. Some methods of relating phenomena to be measured to electronics are considered in this paper. This is the rapidly expanding field of transducers.

I shall define a transducer as a device which is capable of changing any form of energy into an equivalent electrical current or voltage. An idea of the scope of the abilities of transducers was stated by Carl Berkley[1] as follows: "In nearly 20 years of oscillography, the Allen B. Du Mont Laboratories has yet to find a phenomenon which is incapable of conversion into a suitable electrical signal." Although there are numerous applications where other techniques have proved to be more simple, transducers are finding wide use.

The purpose of this paper is to indicate the principles of transducer operation and to discuss their application in a number of problems arising in the field of biology. A more detailed and extensive work in this field entitled *Transducers* is available from the Allen B. Du Mont Laboratories, Inc., 760 Bloomfield Avenue, Clifton, N. J. It lists about 300 industrial manufacturers and 1500 of their products, together with data on the most important design characteristics and uses of these products. It is provided with a complete index and reference section, as well as a written discussion of each subject.

Whereas electronic handling, manipulation, amplification, and control have been highly developed, the transducer which must supply the system with information has not been fully exploited.

The physical principles upon which all transducers operate may be classified in eight broad categories which I shall discuss, illustrating these principles and techniques for using them.

(1) The resistive-type transducers may be further divided into two groups: those whose resistivity or physical structure is varied by the phenomena to be measured, and those which change in value of resistance by means of a mechanical link. The potentiometer is in the latter group These devices are widely used in servo systems and as manual and mechanical controls. In the former group is the strain gauge, whose cross-sectional area and length, when varied, produce changes in the elements' resistance (FIGURE 1). These transducers find wide application in measurements of tension, force, weight, and torsion where they are attached directly to the members under investigation.

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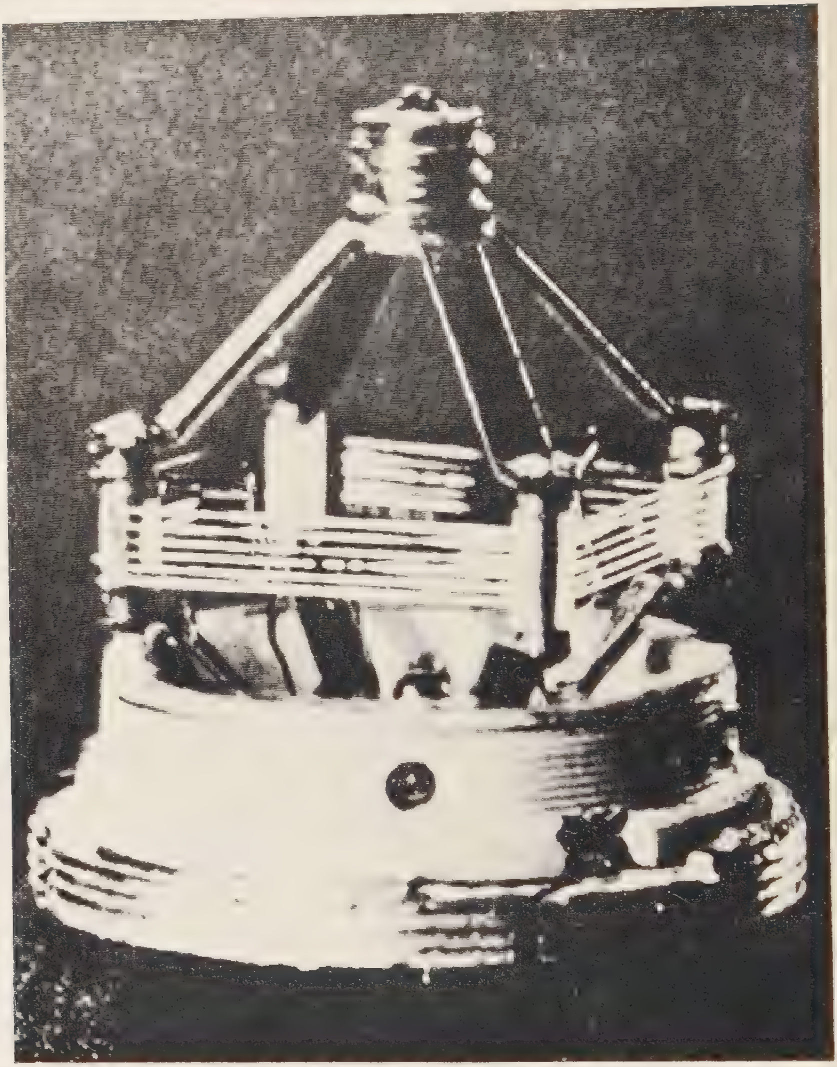

FIGURE 1 An unbonded strain gauge unit used in a pressure pickup. Type 4-310 pickup made by Consolidated Engineering Corporation.

Coupled with other elements, they find use in measurement of acceleration, vibration, temperature, and pressure.

A very excellent transducer for humidity in this group is made by saturating a cotton or absorbent fiber in saline solution (FIGURE 2). The resistance of this fiber will vary proportionally with the amount of moisture it absorbs. From a similar point of view, the human body may be thought of as a transducer. The heart and brain of most animals (both vertebrate and nonvertebrate) produce electrical voltages. The major problems arising from the use of animal organisms include the difficulty of making good contact (electrodes)

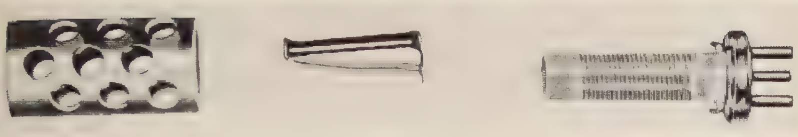

FIGURE 2. Exploded view of a temperature-humidity sensing element. Type TH-2, made by American Instrument Company, Inc.

and the weak signals which are generated. By means of fairly elaborate electronic circuitry, however, measurements from these sources have reached into the noise level. The differential vectorcardiograph and electroencephalograph have resulted from the application of this principle.

It is possible to base pH indicators upon changes in resistivity of various fluids. By measuring resistance of some solutions under varying voltage conditions, the chemical composition of solutions can be determined, as in the polarograph.

(2) Capacitive-type pickups usually rely on variations in the dielectric, as in the case of materials flowing between conductors; on the separation between conductors, as in the case of some velocity and diaphragm type pressure pickups; or on the amount of conductive surface separated by a fixed dielectric. The most sensitive velocity pickup yet devised is based upon the latter principle. It was recently developed at the National Bureau of Standards. In the case of pressure measurements by means of a diaphragm, it is possible to avoid obstructing the course of flow and have only minimal contact with the fluid from which measurements are to be taken.

(3) Magnetic pickups generally have the advantage that no contact with the object from which the measurement is to be made is necessary. FIGURE 3 shows a cutaway view of a differential transformer. The primary and secondary are wound on a form into which the core is free to move. FIGURE 4 shows the complete differential transformer in which motions of the core are detected as variations in the characteristics of the transformer. A permanent magnet can be made into an excellent pickup, since any magnetic material passing through its field will induce a voltage into a coil wound on the permanent magnet. This induction is a generator effect. Certain materials, particularly

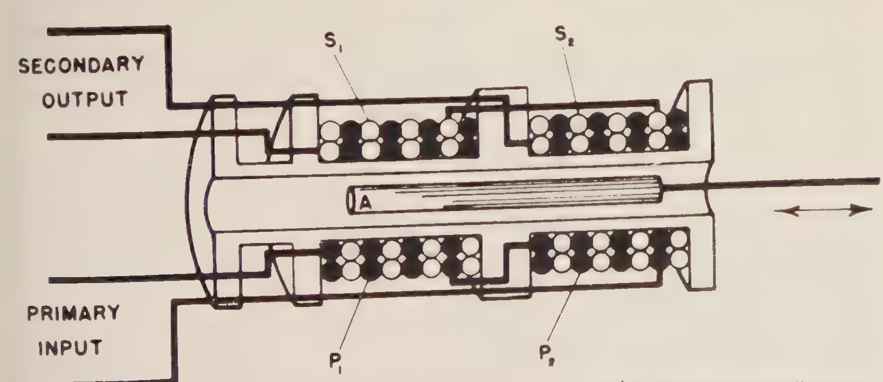

FIGURE 3. "Atcotran" Type differential transformer made by Automatic Temperature Control Company.

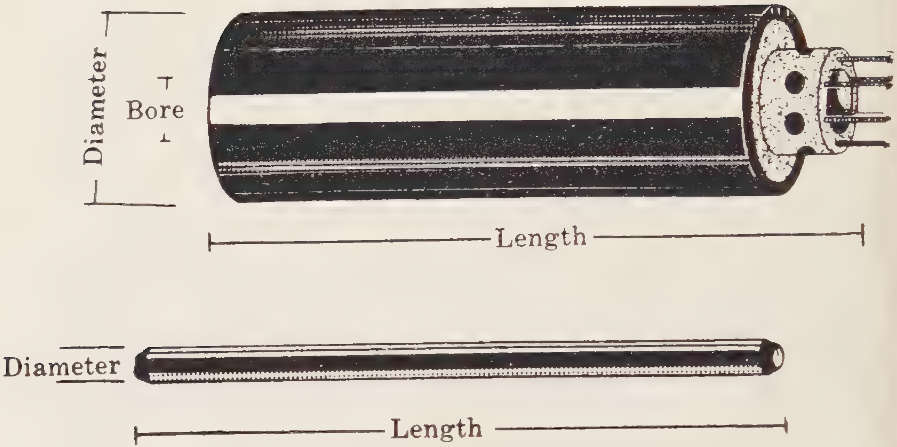

FIGURE 4. Differential transformer made by Automatic Temperature Control Company.

nickel and cobalt, exhibit magnetostrictive effects; that is, when mechanical stresses are impressed upon these materials, they generate electrical voltages between their faces.

(4) A popular group of transducers operate upon piezoelectric principles, which are somewhat similar to the magnetostrictive effects. Certain materials, when stressed or mechanically deformed, generate electrical voltages between their faces. In addition to naturally occurring piezoelectrical material, such as quartz and tourmaline crystals, there are a number of recently developed synthetic materials available, most of which have increased sensitivity. Among these are rochelle salts and barium titanate. FIGURE 5 shows a barium titanate accelerometer. Crystals of this sort are used in some of the most sensitive transducers, and have an extremely high frequency response. Crystal transducers are commercially available for pressure vibration, acceleration, force, and sound measurements.

(5) The most versatile transducing principle is the photoelectric effect. Transducers devised on this principle are almost unlimited in their ability, though frequently cumbersome. They permit us to locate an analytical device in place of the human eye which can be made to do anything which the eye can do and more. Their sensitivity has been extended into the infrared and ultraviolet. They may be used with a separate light source or operate radiation from objects as in pyrometry. Their sensitive member is composed of materials which have the ability to emit electrons when bombarded by photons of light. These electrons form a current which may be amplified to provide a useful output. FIGURE 6 shows a group of commercial multiplier phototubes which are capable of amplifying the primary signal two million times.

By means of a fixed light source and a photocell, the motion of an opaque member may be measured without physical contact. The color or spectral responses of materials may be sensed by direct illumination or reflection. Moving light sources in scanning mechanisms are also being used successfully.

(6) Thermoelectric transducers can be based upon any of the following

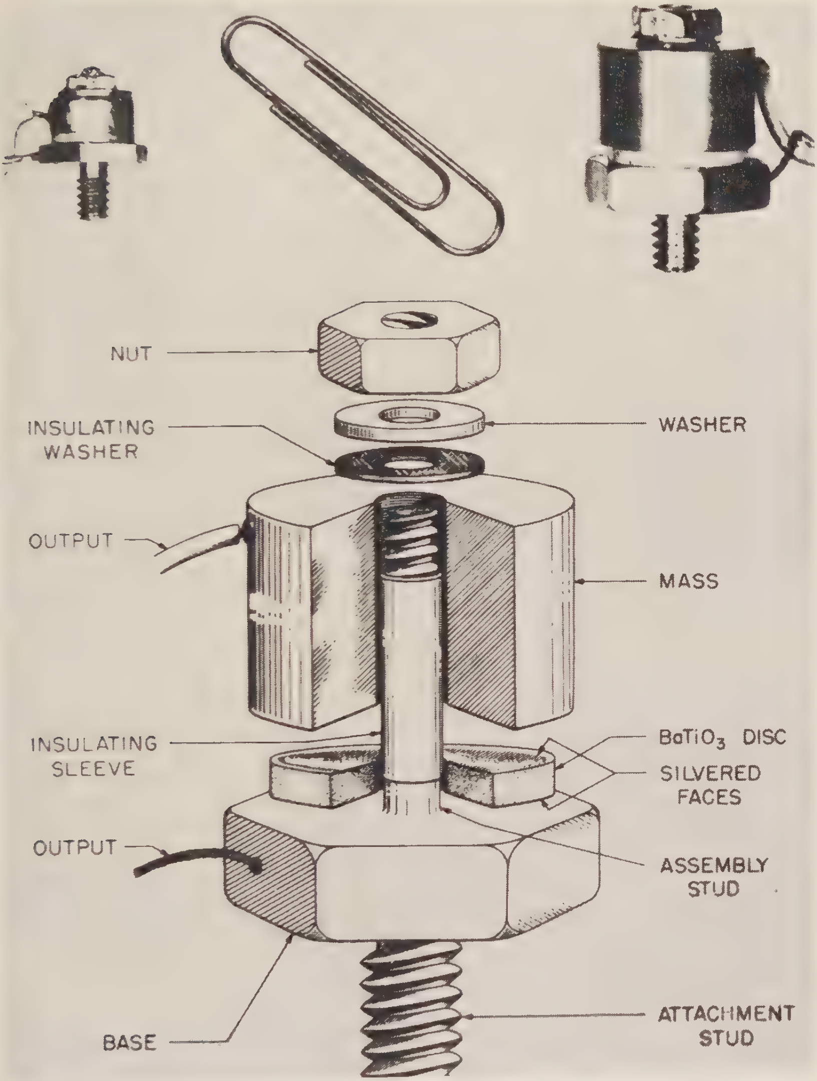

Figure 5. National Bureau of Standards ceramic accelerometer

principles: (a) most materials exhibit a change in resistance which is a function of temperature; (b) they also change color or wave length of radiation with temperature; (c) differences in the expansion characteristics with temperature are used in bimetal strips better known as thermostats; (d) certain materials exhibits a difference in work function with variation in temperature, that is, they generate a varying voltage when in contact with one another at different temperatures; finally (e) a confined gas with a pressure pickup may be used to sense temperature.

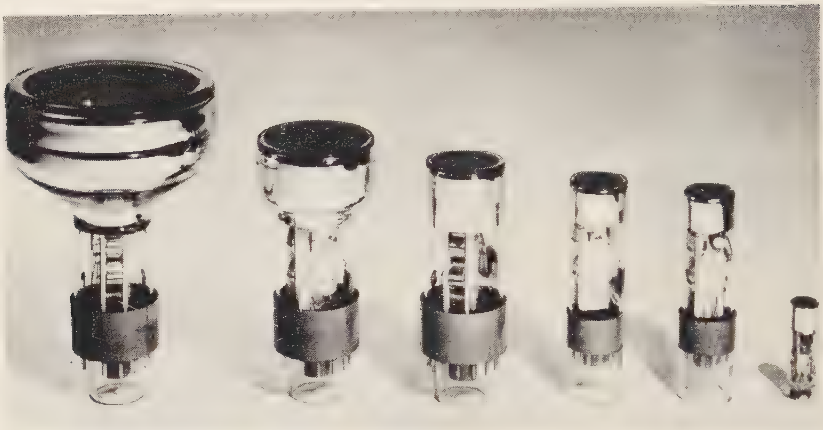

FIGURE 6. Multiplier phototubes made by Allen B. Du Mont Laboratories, Inc.

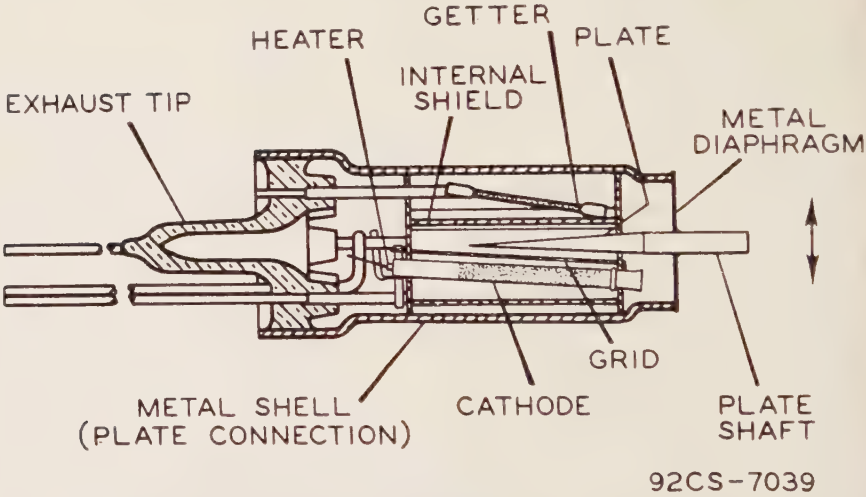

FIGURE 7. Cross-sectional view of Type 5734 made by Radio Corporation of America.

(7) A rather highly specialized group of transducers is based upon electron effects. Among these devices are the cathode-ray tubes which are particularly sensitive to magnetic fields and special electron tubes. FIGURE 7 shows the Type 5734 tube manufactured by the Radio Corporation of America. It has a movable element which may be coupled mechanically through the metal diaphragm. Motion of this element produces variations in the electrical characteristics of the tube itself. Direct translation of motion into an electrical signal with the additional advantage of amplification makes this a most sensitive transducer.

(8) Finally, the most recently developed transducing medium is radioactivity. As work in this field continues, I feel that we shall find vastly larger

numbers and ranges of applications. The pickups for radioactivity (Geiger-Mueller tubes, scintillation crystals, and ionization chambers) change radioactive radiation into electrical current. These radiations may be detected in quantities many orders of magnitude below any other known signal source. Also, they may be introduced into processes without disturbing them. Methods of

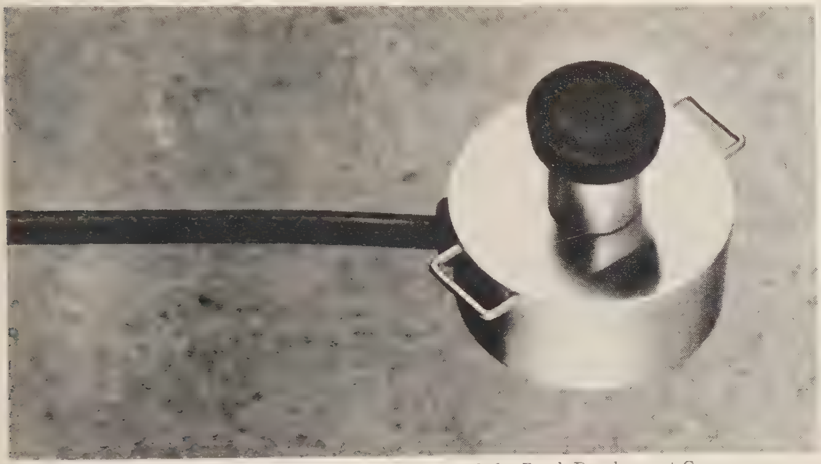

FIGURE 8. DP-1H sensitive heart beat pickup made by Brush Development Company.

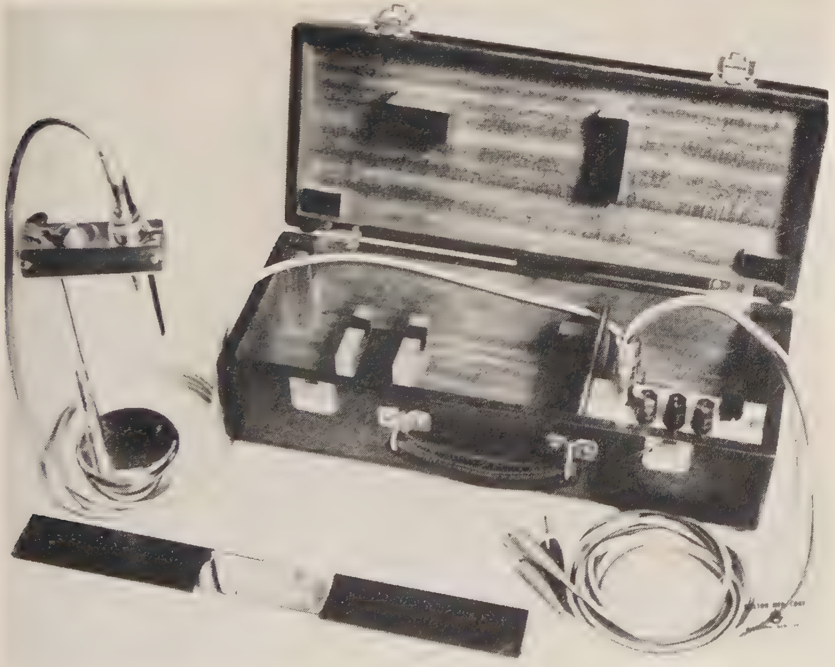

FIGURE 9. Glennite Type M-101-A ballistocardiograph made by Gulton Manufacturing Company.

extending the uses of radioactive tracers are being carefully investigated at the present time.

The applications of all these principles have been extended to every field of science. A considerable amount of time could be spent exploring the possibilities in any given set of circumstances. In the remainder of this paper, I

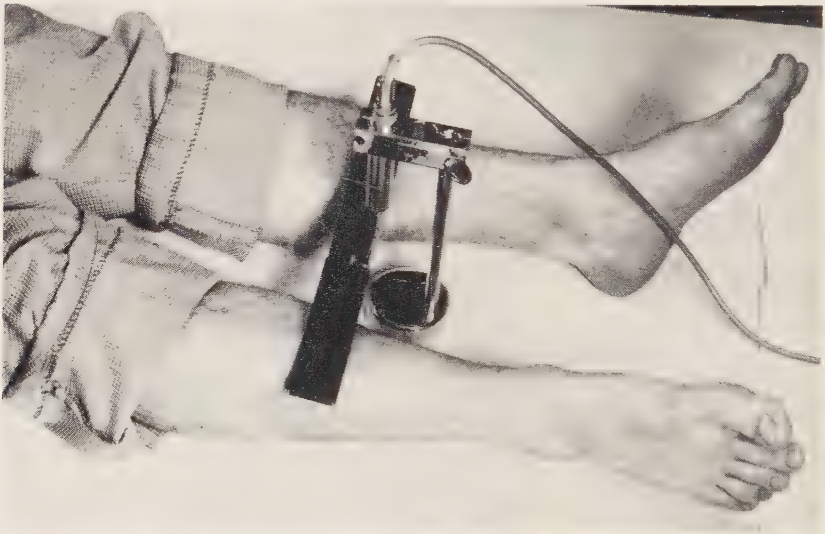

FIGURE 10. Glennite Type M 101-A ballistocardiograph made by Gulton Manufacturing Company.

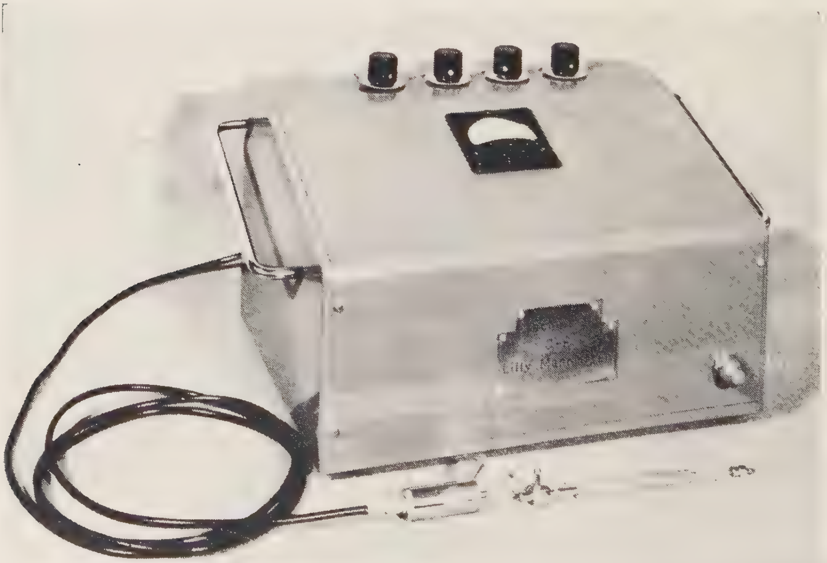

FIGURE 11. Lilly manometer with hypodermic needle pressure pickup made by Technitrol Engineering Company, Inc.

shall discuss the transducers used in some of the measurements and techniques which are of particular interest to the biologist, physiologist, and biophysicist.

FIGURE 8 shows a pressure pickup which is used to sense heartbeat. It is a crystal activated pressure transducer many times more sensitive than the common stethoscope. A commercially available ballistocardiograph is shown in FIGURE 9. The proper method of applying it is shown in FIGURE 10. This device is a sensitive displacement pickup employing a plastic covered knife edge which makes contact with both the patient and a barium titanate transducer. An extremely sensitive and versatile ballistocardiograph has been developed by the National Bureau of Standards. It embodies a velocity pickup operating on magnetic principles. Its versatility is extended by making electronically integrated or differentiated outputs available. This instrument has been used with some degree of success in the clinical evaluation of such conditions as angina pectoris, hypertension, coarctation of the aorta, and coronary occlusion.

Blood pressure may be measured in many ways. FIGURE 11 shows a hypodermic needle which is inserted into the blood stream. The blood enters a small chamber where its pressure against a diaphragm is sensed as a capacitance. Thus, changes in capacitance indicate changes in blood pressure. A microphone has been used to control a servomechanism in the newly developed National Bureau of Standards Physiological Monitor, which detects changes in condition of a patient under anesthetic.[2] It measures and records blood pres-

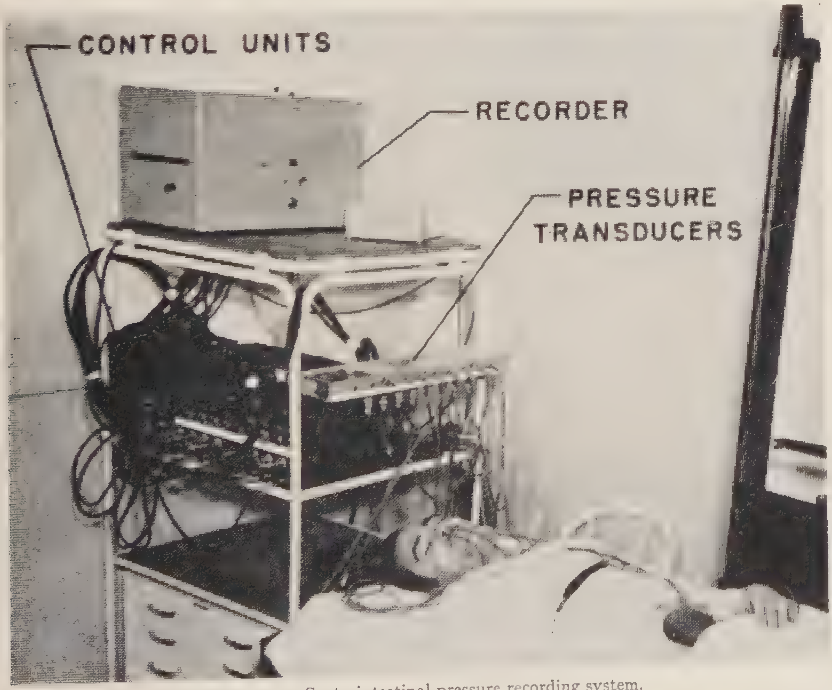

FIGURE 12. Gastrointestinal pressure recording system.

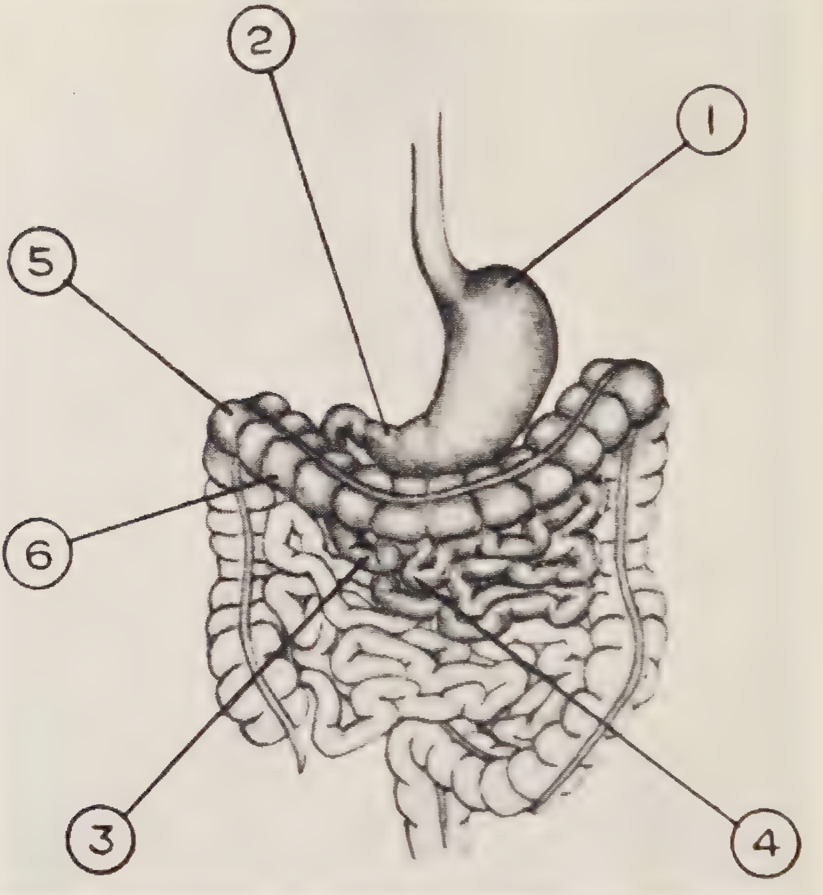

Figure 13

sure, heart beat, and respiration. The servomechanism periodically applies pressure until systolic pressure is exceeded, then gradually reduces the pressure determining both systolic and diastolic pressures. Figure 12 shows a system in which six low-range strain-gauge pressure transducers are involved in the recording of gastrointestinal pressures.[3] First, slightly inflated balloons are located fluoroscopically inside the patient at the different locations shown (figure 13). These balloons are connected through tubes to pressure pickups which detect the gas pressure in terms of electrical outputs, which are amplified to make these recordings a permanent record (figure 14). The pickups in this case, made by Statham Laboratories, Inc., are strain-gauge bridges.

Pickups are widely used for rapid analysis of respiratory gases. Some of these instruments are capable of making a complete analysis of the carbon dioxide, oxygen and other gas content in the interval of a single breath.

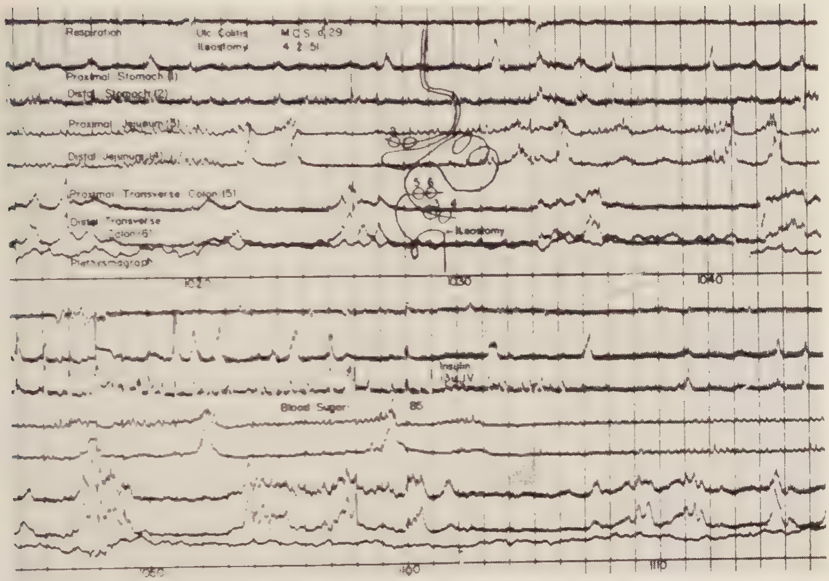

FIGURE 14. Section of record showing simultaneous recording of motor activity in the stomach, small bowel, and colon. Tandem balloons were introduced to the respective levels under fluoroscopic control. The transverse colon in this case was intubated through the distal stoma of a double barreled ileostomy in a patient with ulcerative colitis. This section is taken from the very beginning of the record to show that the tracings of the respective functions may be spaced evenly in relation to each other.

Radioactive tracers are being used to analyze different conditions in living bodies. Thyroid conditions are being investigated with radioactive iodine in this manner. In these applications, radioactive tracers are injected into the system to be investigated, and their presence at various locations is detected with the conventional radiation transducers. The dissemination or travel of the "tagged" elements may be followed throughout the organism.

A transducer which transmits an ultrasonic frequency wave by means of crystal or piezoelectric transducer is shown in FIGURE 15. Information on this system was published very recently in one of our popular magazines.[4] The transducer first transmits energy in short sharp pulses, then detects echoes from tissue layers, bones, viens, nerves, *etc.* These echoes may be identified by their characteristic reflections. This device seems promising for use in detecting cancerous growths.

Photocells or light transducers are the basis of the field of spectrophotometry which is finding wider use in medical investigations. Such a system has been used successfully to observe the circulation of the blood *in vitro.*[5] Spectral analyses were made to determine the condition of the blood in the same manner. A cell condition detection method which uses nuclear fluorescence of the cells under special conditions has recently been published.[6] Efforts are being made to relate this effect to cancer studies. An automatic blood cell counter has also recently been publicized.[7] Both of these devices use light transducers as

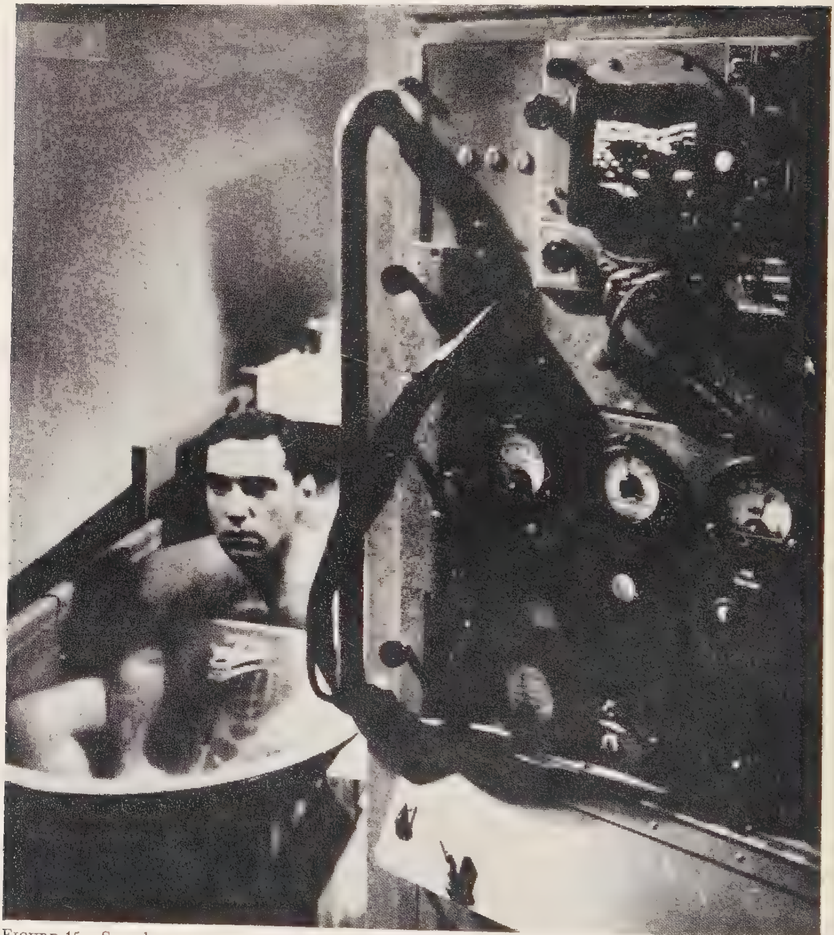

FIGURE 15. Sound-wave portrait in the flesh. The subject sits in the tub as sound waves, streaming into him from behind, record the inner tissues of his back on the scope (top).

their fundamental sensing elements. In the first case, a television camera chain is used and, in the second, a photomultiplier.

Temperature transducers involving thermocouples in the form of hypodermic needles have been constructed.[8] Techniques have been tested for measuring osmotic pressures with strain gauge transducers.[9] Cardiac catheterization[10] is an informative diagnostic procedure using a small sensitive pressure pickup, the terminus of which is introduced into the heart through a convenient peripheral vein. The sensitive element, the Hathaway PS-18 catheter pressure head, is only $\frac{3}{32}$ inch in diameter.

As the science of instrumentation develops, transducers will continue to become available to make the most difficult measurements to the required degree of accuracy. In addition, we may confidently expect transducers to quantitate a host of presently unknown phenomena.

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CONSTRUCTION AND APPLICATION OF MEMBRANE ANALOGS

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Historical Background

Basic to the study of mechanics, vibrations, elasticity, and acoustics, the mathematical analysis of membranes was begun by Poisson in 1826 and was synthesized by Lord Rayleigh.[1] Following a suggestion made by Prandtl[2] in 1902, the static membrane was widely used in the study of torsional stresses and, in this application, received its greatest development. T. J. Higgins[3] made an exhaustive survey of this work in 1945. Since the advent of rapidly applied variational methods and finite difference procedures,[4] the use of the membrane analog is chiefly tutorial in stress problems.

More recently, electron ballistics and the design of vacuum tubes have presented problems which led the group at Philips of Eindhoven to quantitative use of the membrane,[6, 7, 8, 9, 10] even to the extent of evaluating a nonuniform distribution of sources. Though not as popular as the electrolytic tank, the membrane analog is being used to solve modern electrical engineering problems in network synthesis,[11, 12] and in electrode design. Because they lie within the author's experience, it is from these fields that the illustrations of this paper are drawn. Biologists will see their own applications, as exemplified in the famous two-dimensional field maps obtained by Lorente de Nó[13] in his studies of the propagation of nerve impulses.

Introduction

The deflection z of a thin elastic membrane under constant surface tension satisfies a partial differential equation which, for small deflections, reduces to Laplace's equation in two dimensions.

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} = 0$$

Geometrically, the sum of the curvatures of the membrane is zero at every point. Mathematically, the elevation of the membrane may be interpreted as potential in hydrodynamics, and in electric and magnetic fields, or as temperature in heat-flow problems. This is the case in which the membrane is subjected to uniform pressure on both sides of the sheet, and in which the corresponding potential or temperature field is without distributed sources. As will be illustrated later, when there is a pressure difference on the two sides of the membrane, the differential equation reduces to Poisson's equation, which applies to fields containing distributed sources. In applying the analog, one simulates the boundary conditions and source distributions of the problem and then measures the elevation and slope of the sheet as a function of position.

Materials and Construction

While many workers have employed soap films, these devices are obviously temporary and fragile. Further, their imperfections are frequently more serious than the nonuniformities[14] in rubber sheeting. Of several possible sources of rubber sheeting, the one which is the most readily available and the most practical is surgical rubber or rubber dam. The sheet should be light in color and from 7 to 10 mils in thickness. Thickness sheeting has a greater sag for a given stretching force, and greater forces are required to establish the boundary conditions.

The simplest frame is a quilting hoop, commonly made of two nesting wooden hoops, like an overgrown embroidery hoop. For any sort of quantitative work, a more substantial frame is required. Anything which is stiff enough to provide an accurate plane boundary, and will remain quite level when the rubber sheet is displaced from the plane of the frame, will be found satisfactory. For the illustrations in this paper, the frame is a heavy steel hoop, 32 inches in diameter and with a 1-inch-square cross section, as may be seen in FIGURE 1. Round frames have been found superior to square frames in achieving a uniform initial stretching, which is necessary for accurate results. Square frames are superior for a problem calling for a free boundary.[6]

As an aid to achieving uniform tension, the unstretched sheet is laid on a

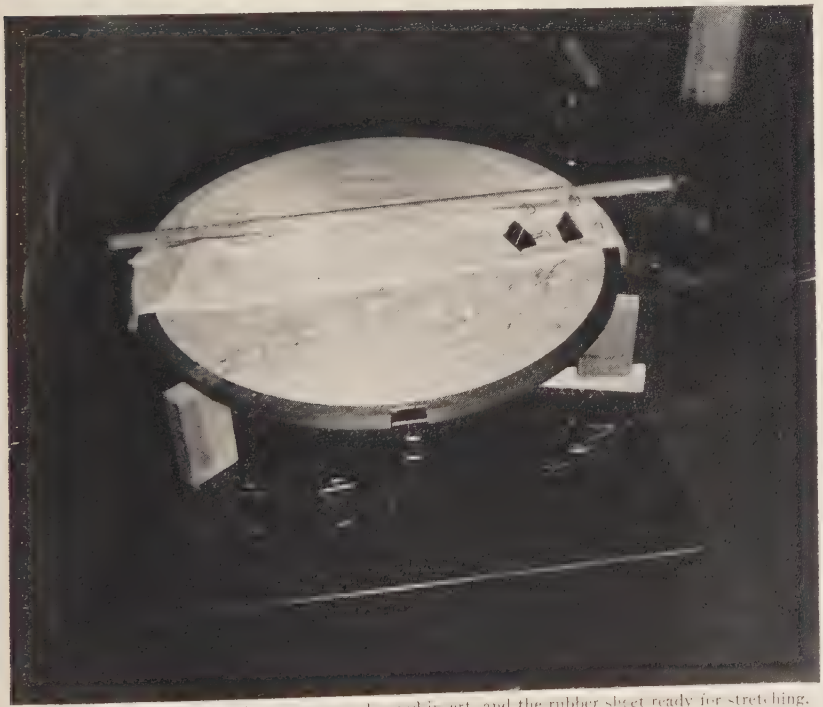

FIGURE 1. The steel frame, the temporary plywood insert, and the rubber sheet ready for stretching. Observe the large binder clips which will hold the rubber sheet on the frame and the adjustable support for the frame.

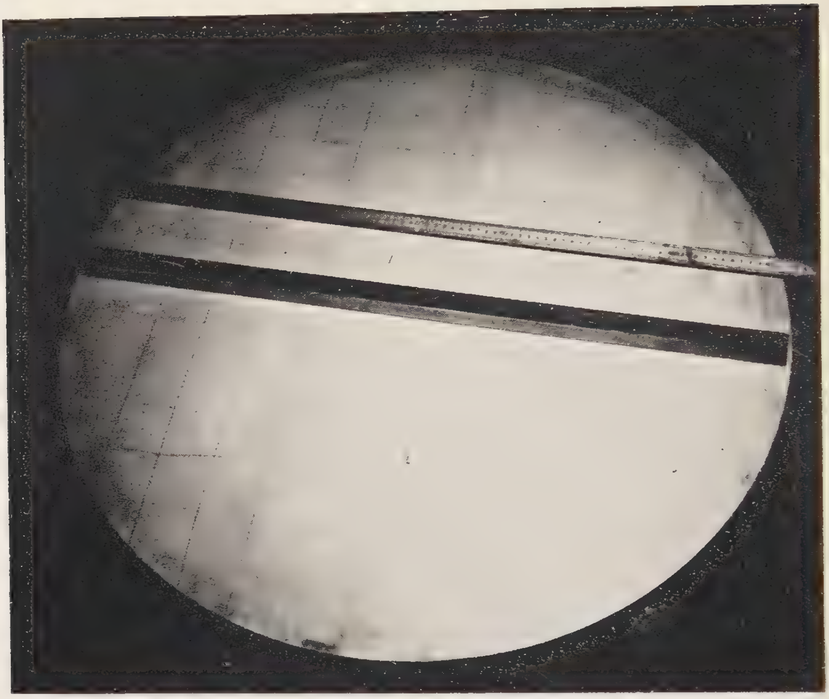

FIGURE 2. The rubber sheet stretched on the circular frame. Before stretching, the sheet was ruled with 2-inch squares, which remain squares only under uniform tension. Lying across the frame is a 1-inch steel bar with finished surfaces which is useful for checking the sag of the rubber sheet, and for aligning the frame with contours cast by a slide projector.

drafting table and ruled with perpendicular lines about two inches apart. Under uniform tension, the resulting squares remain squares, as may be seen in FIGURE 2. In stretching the sheet on the hoop, it is convenient to work on a table rather than on a bare hoop. A table can be made by fitting a round plywood sheet inside the hoop. Ruling the plywood table with another set of 2-inch squares provides guide lines during the stretching process. Because the table supports the sheet in the initial stages, it is a great time saver. Later, the plywood table can be dropped down through the hoop, leaving the stretched sheet supported only by the hoop. FIGURE 1 shows the steel frame with the plywood circle in place and the rubber sheet laid over the plywood. Here, too, are shown the binder clips used to clamp the rubber sheet to the frame. While clamping rings can be used, many workers have found these binder clips satisfactory provided enough of them are used to cover practically the entire frame.

During the stretching process, the most rapid procedure is to work with the two cross-section lines which have been placed to intersect at the center of the sheet and, as the stretching progresses, to keep these two lines straight. How much stretching is needed depends on the elasticity of the rubber. What one needs to achieve is sufficient tightness so that the sag of the sheet under its own weight is negligible. For a number of the rubber materials which have been used, the sheet is stretched about 15 per cent at the frame, and the corresponding sag at the center is kept to less than one-tenth inch.

The stretched sheet is shown in FIGURE 2. Observe that, because the binder clips are not in continuous contact with the frame, the tension is not uniform near the edge of the sheet, but that the tension evens up rapidly away from the edge. Evidence of this status is the fact that the ruled lines on the sheet are quite straight.

There are a number of ways of establishing the boundary conditions and, since these depend on the problem being attacked, they will be illustrated by examples rather than by specific discussion.

Lighting Techniques

Before describing applications of the membrane analog to problem solutions or illustrations, I wish to describe two lighting techniques which add much to the usefulness of the membrane. With a given set of boundary conditions or source distributions, it is the elevation of the sheet as a function of position which contains the desired information. At each point of the sheet, then, one requires the relationship between three coordinates. While these relationships can be measured in many ways, the most rapid means of obtaining and recording the information is to cast the coordinate locations onto the sheet optically. To establish the elevations, the sheet is covered with a field of light which consists of horizontal planes of light and darkness. The intersection of the sheet with these planes is then seen by the eye (or by a photographic film) as contour lines of equal elevation, which correspond to equipotentials or isothermals in corresponding two-dimensional physical problems. The horizontal planes of light and darkness are created by placing into a projector a slide which is made from a ruled grating. Suitable gratings for this purpose may be obtained from the Edmunds Scientific Corporation in Barrington, N. J., ruled on glass. A ruling of 175 lines per inch has been used in the illustrations in this paper, and is close to the limit of the resolving power of the average projector lens.

The other two coordinates are cast onto the sheet by a projector located directly over the sheet. A slide can be made by photographing a sheet of cross-section paper, preferably using a negative rather than a positive. The projector used here was a simple home type with a 100-watt bulb operated at about half-rated voltage. This wattage gives enough light and greatly extends the life of the bulb. Because it is operating in a horizontal position, the bulb burns out quickly at full voltage.

To get the idea across more quickly, the statement was made that the sheet is illuminated by *horizontal* planes of light and darkness in order to obtain the elevation of each part of the sheet in terms of contours of equal elevation. But the lighting supplied by the projector consists of planes of light and darkness which are not parallel but intersect. However, when the maximum horizontal dimension on the sheet itself is a small fraction of the distance to the projector, the errors introduced are small, and corrections can be made as is shown in the analysis in the APPENDIX, page 935.

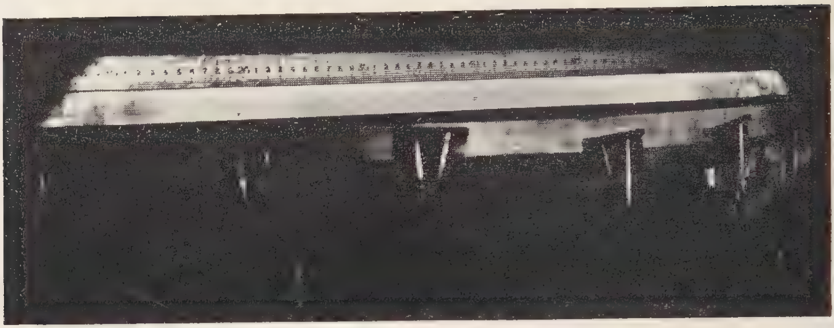

FIGURE 3. Illustrating the method of aligning the planes of light and darkness with the frame which holds the stretched rubber sheet. Under the meter stick is a one-inch steel bar covered with parallel lines cast by a slide projector in the foreground.

Alignment of the Sheet and Checks of Accuracy

It is not necessary, and it would indeed be quite difficult, to have the frame which holds the rubber sheet absolutely level and then to level the central plane of the beam from the horizontal projector. All that is necessary is that the plane of the sheet lie within one of the planes of light or darkness cast by the horizontal projector. This alignment is relatively easy to achieve. The projected beam is set up approximately level, and at the same elevation as the plane of the sheet, which is supported at three points several inches above a stable desk or table. The two front supports are of fixed and equal height, while the rear support (away from the projector) is made adjustable. The slide holder in the projector is constructed in turret form, so that the slide can be rotated in the holder. The first step in the alignment procedure is to place a plane surface across the beam over the two front supports, or at the center of the frame as illustrated in the oblique view of FIGURE 2. In this figure, and also in FIGURE 3, the plane surface mentioned above consists of a 1-inch steel bar with finished surfaces. Now the turret slide holder is rotated until the lines cast onto the steel bar are parallel with the plane of the frame holding the rubber sheet, as illustrated in the eye-level photograph of FIGURE 3. Turning the steel bar 90 degrees, until it is almost parallel with the projector beam, the rear support for the frame is now adjusted to achieve alignment in this direction. This leveling procedure takes only a few minutes and, if the set-up can be left undisturbed, the procedure need not be repeated.

To check the accuracy of the sheet, the following simple procedure has been used. In a Laplacian field, when a potential difference is maintained between concentric cylinders, the potential distribution is logarithmic with respect to the radius as measured from the center of the cylinders. When the two cylinders are not concentric, the potential distribution is logarithmic with respect to the distance from a point slightly off the center of the inner cylinder.[15] If the inner cylinder is very small, however, the displacement of this point from its center is negligible. In FIGURE 4, the sheet is elevated about two inches above the frame by a piece of ¼-inch hardwood doweling. In this figure, the contours of elevation can be seen as shadows caused by the intersection

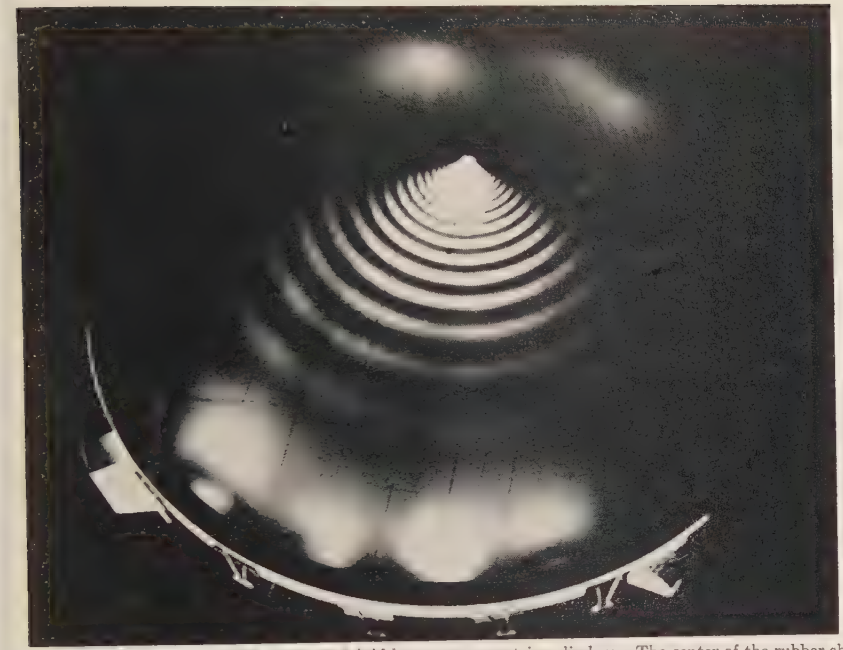

FIGURE 4. Oblique view of the potential field between concentric cylinders. The center of the rubber sheet is held in an elevated position by vertical rod. The circular shadows are contour lines at equal increments of elevation and are cast by a ruled grating in a slide projector located well into the foreground.

of the elevated sheet with the planes of light and darkness cast by the slide projector. Viewed from directly above, the contours are circular. In FIGURE 5, the overhead projector has been turned on and the camera moved to a position in which it looks vertically down onto the sheet. Using the cross-section lines to determine the horizontal distances and either the edge or the center of successive circular shadows to determine equal increments of elevation, the accuracy check consists of recording the observed elevation along a radial line and plotting the potential increments against the radius on semilogarithmic paper, as shown in FIGURE 6 (in making this measurement, it is helpful to use a "Variac" to control the voltage on the overhead projector in order to keep the two sources of illumination at about the same intensity on the part of the sheet being examined).

In FIGURE 6, the straight line represents the theoretical curve of elevation versus radius from the center, while the points represent observations from the contour lines and the projected coordinates. On the upper part of the curve, the contour lines are sharp and the errors are less than 3 per cent. On the lower part of the curve, the contour lines are quite broad and diffuse, so that it is hard to observe just where the edge of the line actually is. The maximum error is about 10 per cent. In this sample accuracy check, a single focusing of the contour projector was maintained and, further, the field of interest is rather large. When a smaller field is examined, the measurements have

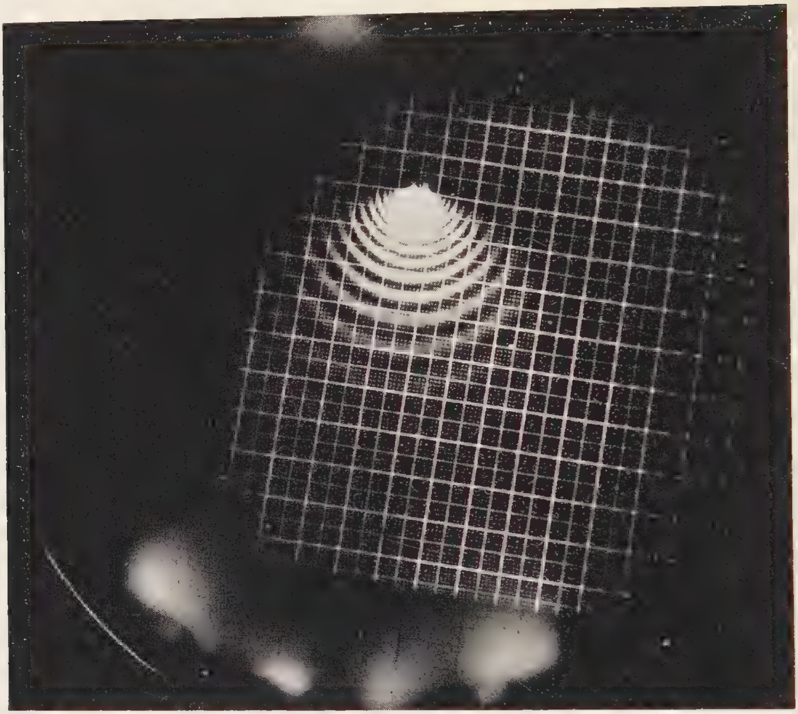

FIGURE 5. An overhead view of the field illustrated in FIGURE 4, with additional lighting from an overhead projector containing a slide ruled with cross-section lines. These cross-section lines provide a coordinate system in the plane of the rubber sheet.

been made within 3 per cent optically, and within 1 per cent by direct scaling. The latter figure indicates that the accuracy of a rubber sheet compares favorably with the electrolytic tank.

In applications more elaborate than those used for the accuracy check described above, the fact that the model has finite dimensions introduces errors. These errors can be accounted for fairly simply when the frame which holds the sheet is circular. For every force exerted at a point on the sheet, the circular boundary simulates an equal and opposite, or *image* force located at the geometric inverse point[15] outside the circular frame. To minimize these effects, the forces applied to the sheet should be kept close to the center of the sheet.

Illustrative Applications

(1) *Coupled circuits.* There is a direct potential analog for the displacements and velocities on any linear oscillating or vibrating mechanical system. This analog is the same one which is applicable to electrical circuit theory,[1] and it arises because we are dealing with linear differential equations with constant coefficients. Here, the frequency response can be illustrated by a planar representation in terms of the location of the resonant and antiresonant

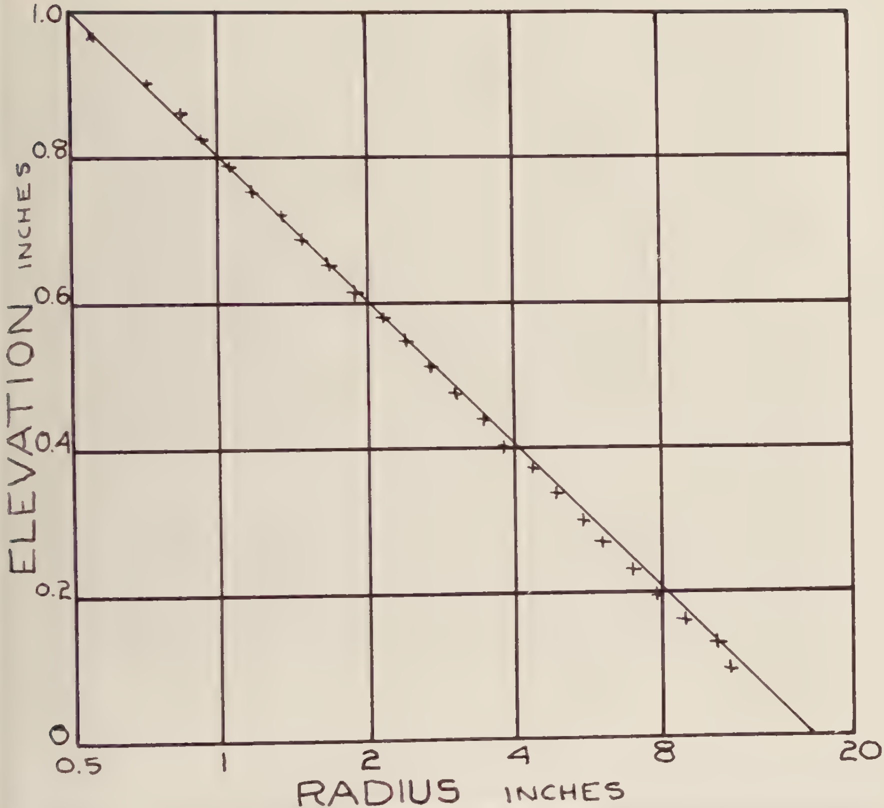

FIGURE 6. A comparison of measured and theoretical elevation levels in the field illustrated in FIGURE 5. The solid line represents the theoretical curve of elevation versus the logarithm of the radius. The crosses are elevations found from the contour lines.

points, often referred to as the *poles* and *zeros* of the response characteristic. In the membrane analog,[12] the poles and zeros are simulated by equal forces, and the elevation of the sheet corresponds to the logarithm of the frequency response, while the slope of the sheet corresponds to the phase rate.

In FIGURE 7, the contour-lighted membrane depicts the potential analog for two coupled circuits or vibrating systems, tuned to the same frequency and having equal damping (taking advantage of the symmetry, here the poles are simulated by the equivalent equal displacements rather than by equal forces).

In FIGURE 7, the elevation and slope information desired lies along a single horizontal line lying below the two points of maximum elevation by a distance determined by the damping of the circuits. Small damping or high Q circuits are those in which the poles are quite close to the real frequency axis. Thinking of the membrane as a mountain with two conical peaks, we imagine ourselves walking along one of the horizontal cross-section lines from left to right. Along the third heavy line below the two peaks, we could walk quite a distance and remain parallel to a contour line and hence at the same elevation. In the

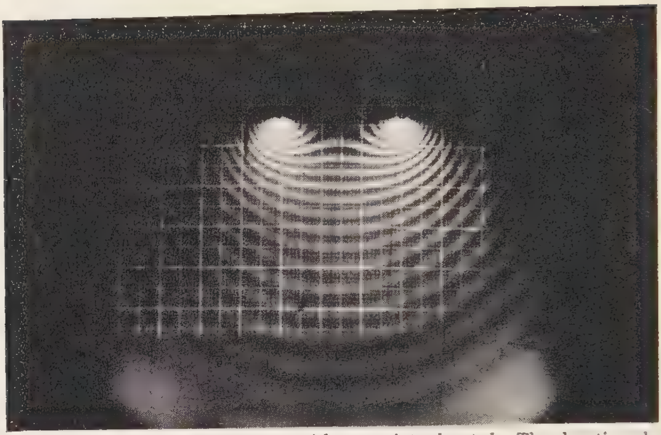

FIGURE 7. Overhead view of the rubber sheet with two points elevated. The elevation along a horizonta coordinate represents the logarithm of the frequency response of two coupled, linear, vibrating systems. The closeness of the horizontal coordinate to the two elevated points is determined by the damping of the systems

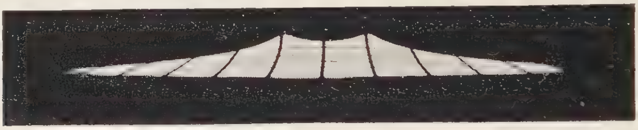

FIGURE 8. A horizontal view of the field illustrated in FIGURE 7, with only the foreground illuminated. The top of the lighted region forms a graph of the logarithm of the frequency response of two coupled circuits tuned to the same frequency.

original coupled-circuit problem, this means that, for this degree of damping. the response of the circuits as a function of frequency is relatively flat over a band of frequencies, a property of considerable importance in the circuitry of television receivers, for example. The same problem is modeled in FIGURE 8, in which the camera looks horizontally at the elevation of the rubber sheet. By lighting from overhead only the foreground, the curve formed by the top of the lighted region gives a vivid portrayal of the elevation of the sheet along a line of interest and represents a plot of the response of the coupled system as a function of frequency for a particular value of damping.

(2) *A dipole.* Equal and opposite forces closely spaced on the rubber sheet simulate a dipole, analogous electrically to a line dipole, and also analogous to closely-spaced source and sink. This important configuration can be established in either of two ways. The first way is to establish it directly, as shown in FIGURE 9. The second is to use the image principle, as shown in FIGURE 10. In FIGURE 10, only the pole of the dipole is used, and the zero potential plane is established as a boundary condition by means of the steel bar. The field configurations in the two figures are identical. Analytically, the field in FIGURE 10 is due to the pole and to its equal and opposite mirror image.

(3) *A cylindrical triode vacuum tube.* A rubber-sheet model of the potentials in a two-dimensional vacuum tube is useful as a teaching aid, and FIGURES 11 and 12 are included to show the simplicity and effectiveness of this application. FIGURE 11 shows the general configuration of the model. The six outer

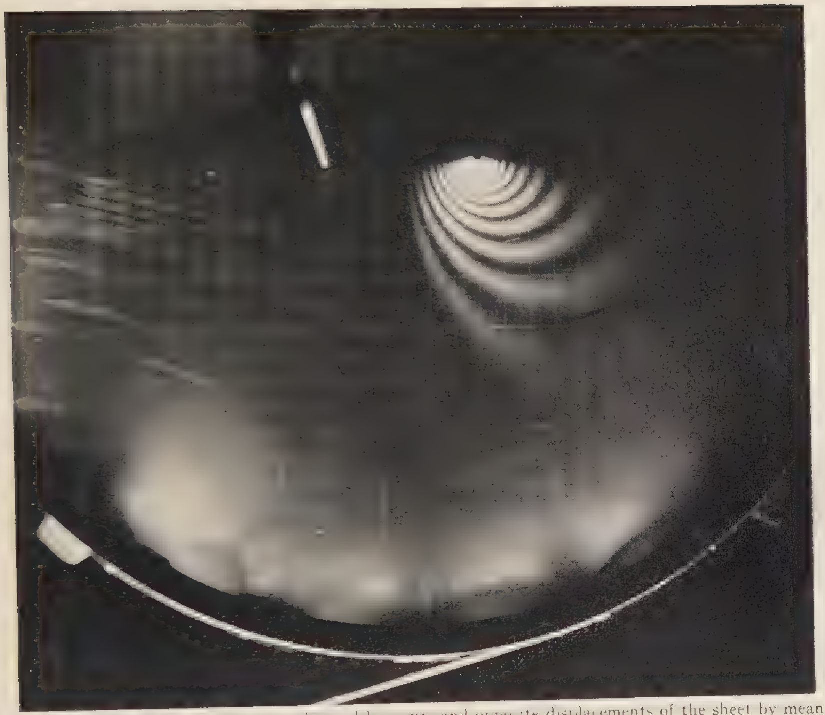

FIGURE 9. The field of a dipole established by equal and opposite displacements of the sheet by means of rods from above and below.

peaks of the hill represent the control grid wires, and the central peak represents the cathode. The circular outer boundary represents the plate. FIGURE 12 is an overhead view looking directly down onto the contours now cast by two slide projectors, one on each side of the model.

(4) *Fourier's heat-slab problem.* FIGURES 13 to 16 inclusive successively show the establishment of boundary conditions of a different character and lead to a portrayal of Fourier's famous heat-slab problem.[18] The boundary conditions may be stated simply. A plane of finite width is maintained at a constant temperature. The region at infinity and along two planes perpendicular to, and in contact with, the constant temperature plane is maintained at zero temperature. The problem is to determine the temperature distribution within the boundaries described. FIGURE 13 shows the establishment of the first boundary condition. The rubber sheet is maintained at an elevated position by a rectangular piece of masonite standing on edge on the table below the rubber sheet. The contours represent the temperature distribution between a hot slab and a surrounding cylinder, and also the electric field around a bus bar in a cylindrical conduit. In FIGURE 14, one of the planes perpendicular to the elevated plane is held at zero elevation by means of a heavy steel bar. As the steel bar is lowered onto the sheet, the equipotentials or isothermals seem to retain their individuality as they move into the new position as required by the new boundary conditions, and this fact is suggestive

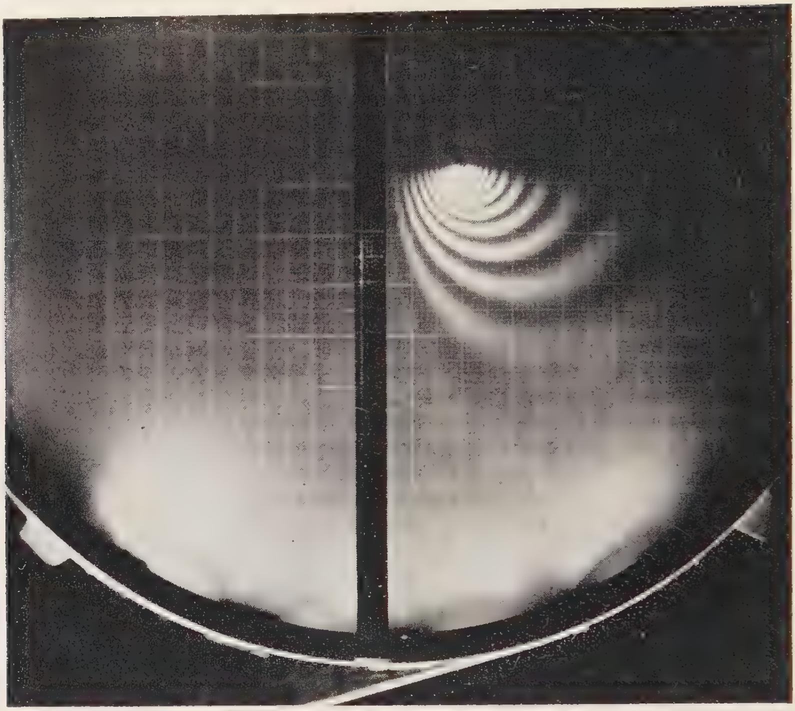

FIGURE 10. The field of a dipole established by the image principle. The wide vertical black stripe in the picture is the top of a steel bar which holds the rubber sheet in a horizontal position. The elevation of the sheet at the right is identical to that in FIGURE 9.

of the conformal transformation which is occurring mathematically. An oblique view of the rubber sheet with the second boundary plane in position is shown in FIGURE 15, while the overhead view which correctly shows the shape of the contours appears as FIGURE 16. Practically, we must be satisfied with a small displacement at the intersections of the plane boundaries lest the rubber sheet be broken.

(5) *A lamellar-flow representation.* In these two-dimensional problems, stream lines and equipotentials may be interchanged. It is thus possible to model some lamellar-flow problems rather easily. FIGURE 17 illustrates this duality of equipotentials and stream lines. The entire frame has been tilted into the beam of light cast by the projector, and the uniform slope of the sheet thus becomes a field with uniform gradient. A cylindrical tube holds a circular region of the sheet in a horizontal position, and the steel bar below the meter stick holds a tangent plane at the same elevation. Potential-wise, this is a model of an equipotential plane with a circular boss on it. From a streamline viewpoint, the plane and the tangent circle are streamlines, and the contours represent the streamlines of electric current around a hole tangent to the edge of a bus bar. From another view, if FIGURE 17 is turned upside down, the plane streamline (below the meter stick in the figure) is the bottom of a

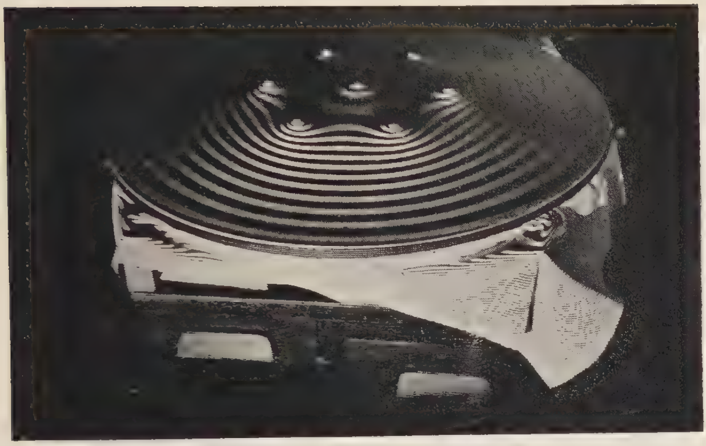

FIGURE 11. Oblique view of the membrane analog of the potential field in a cylindrical triode vacuum tube without space charge. The central peak represents the cathode, the six outer peaks represent the control grid, and the circular frame represents the plate. Here, cathode and grid are at the same potential.

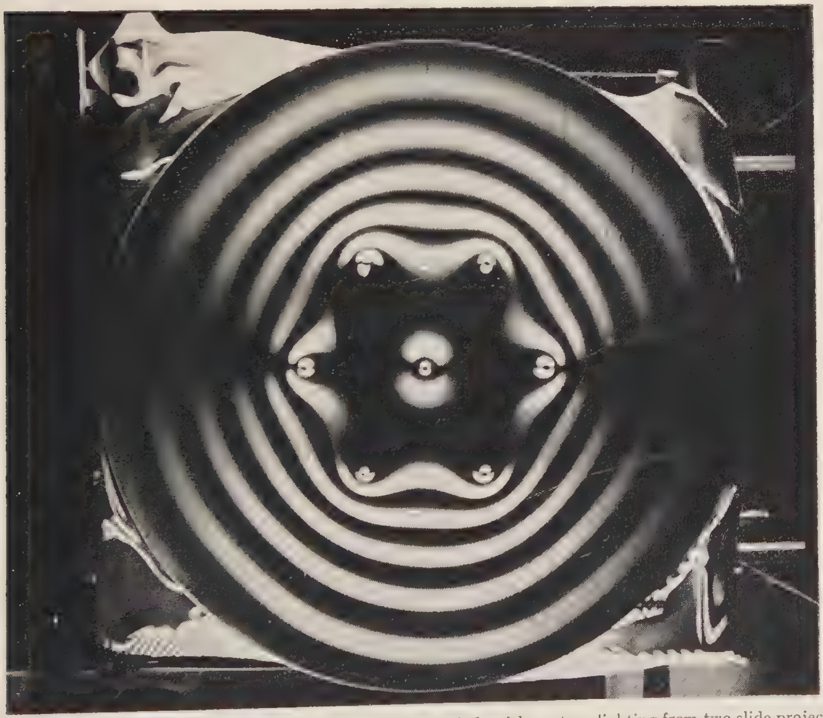

FIGURE 12. Overhead view of the field of a cylindrical triode with contour lighting from two slide projectors located on opposite sides of the model.

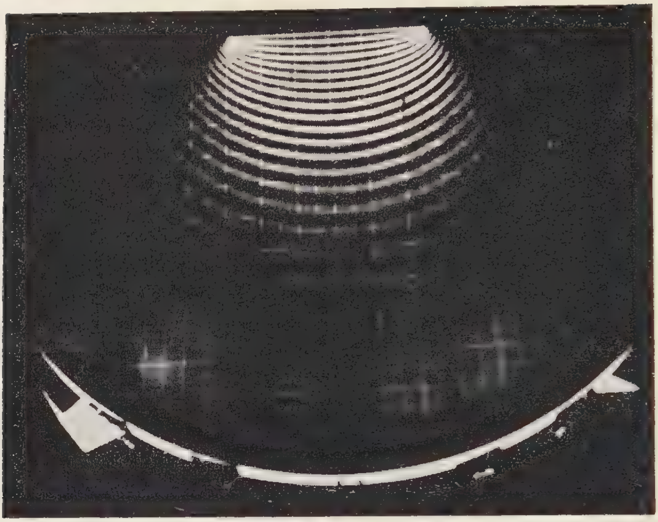

FIGURE 13. The potential field of a plane strip in a cylinder, presented in the text as the first step in modeling Fourier's classic heat-slab problem.

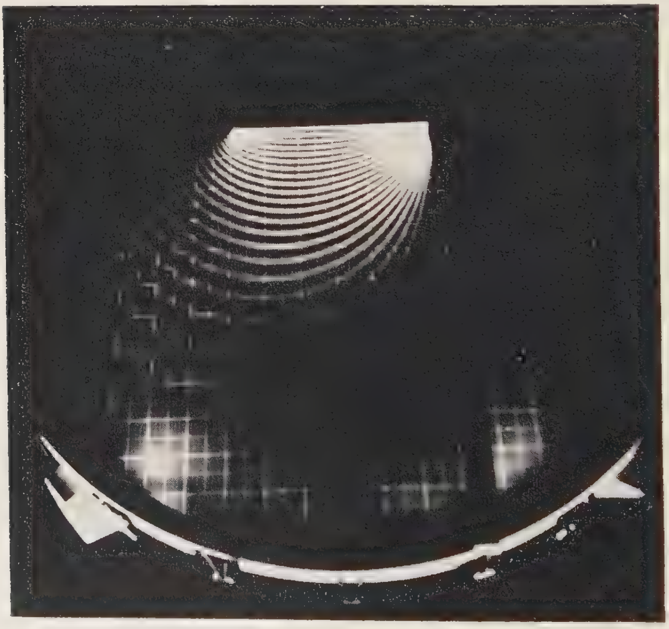

FIGURE 14. The second step in modeling Fourier's heat-slab problem. An oblique view of the field between a plane strip and an almost contiguous perpendicular plane. The plane is simulated by a steel bar which holds the rubber sheet in the plane of the frame at the right of the lighted region of the figure.

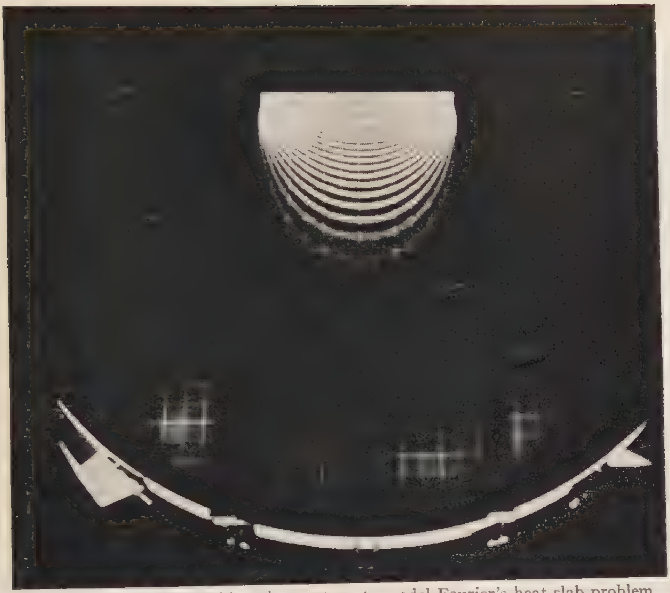

FIGURE 15. Oblique view of the rubber sheet set up to model Fourier's heat-slab problem. At the top of the lighted region of the picture the sheet is held in a uniformly elevated position. Perpendicular to the elevated strip, the sheet is held in the plane of the frame by two heavy steel bars which are vertical in the picture.

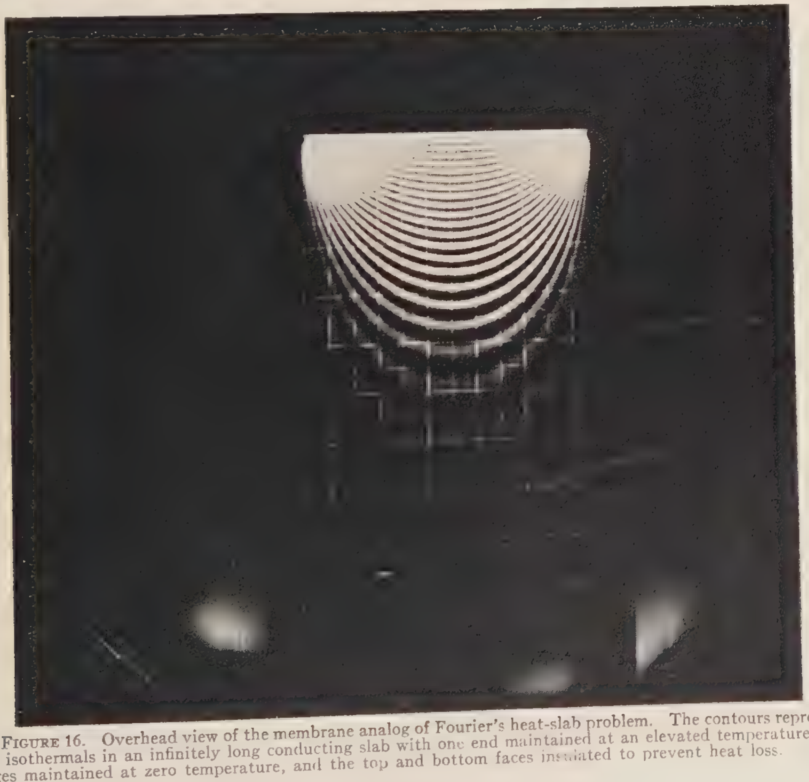

FIGURE 16. Overhead view of the membrane analog of Fourier's heat-slab problem. The contours represent the isothermals in an infinitely long conducting slab with one end maintained at an elevated temperature, the edges maintained at zero temperature, and the top and bottom faces insulated to prevent heat loss.

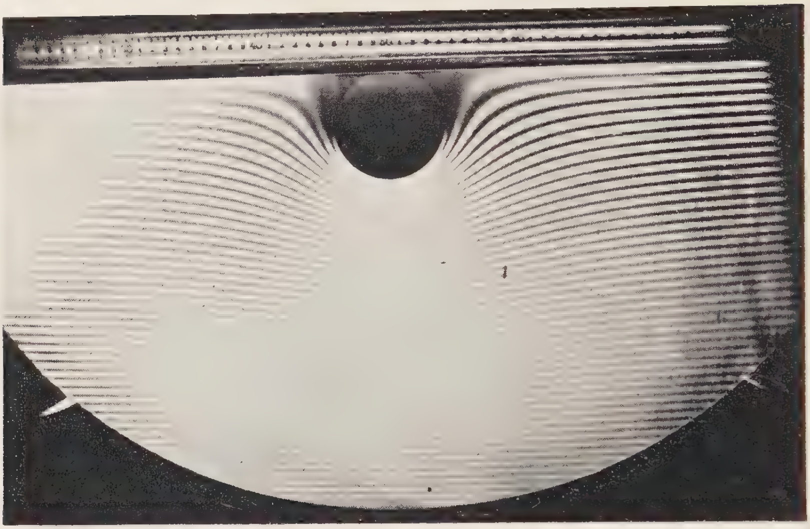

FIGURE 17. The rubber sheet set up to model a lamellar-flow problem. The rubber sheet and its frame is tilted into the beam of light cast by the contour projector in order to establish a uniform field. At the top, the elevation is held constant along a plane and over the surface of a tangent circle. See text for interpretations.

stream of nonviscous fluid, while the circle represents a cylindrical obstacle lying on the bottom of the stream.

(6) *A Poissonian field.* In all of the illustrations above, Laplacian fields have been modeled. Boundary conditions have been established, and sources have been confined essentially to points. Distributed sources are *Poissonian*, which is to say that they are described by Poisson's equation, of which Laplace's equation is a special case in the absence of distributed sources. When a membrane is subjected to uniform pressure on one side, the pressure corresponds to uniformly distributed sources, or to a uniformly distributed charge in the electric field. The field arising from uniformly distributed sources within a triangular region is represented in FIGURE 18. The triangle, distinguished by its straight sides in the figure, is formed by the edge of a triangular pan made of sheet steel which has been forced up against the rubber sheet. By this procedure, the rubber sheet forms the lid of an air-pressure vessel. Pressure is maintained in the pressure vessel by connecting it with rubber tubing to a regulator and compressed air-supply line. This method is similar to the technique used in studying torsional stresses as mentioned at the beginning of this paper. The contours represent the lines of equal stress potential in a triangular shaft under torsion. Outside the triangular region, the field portrayed in FIGURE 18 represents the electric field between a triangular inner conductor and a circular outer conductor.

Comparison with Other Analogs

While a strict comparison of one analog against another must be made for the individual problem under attack, there are some general comparisons of

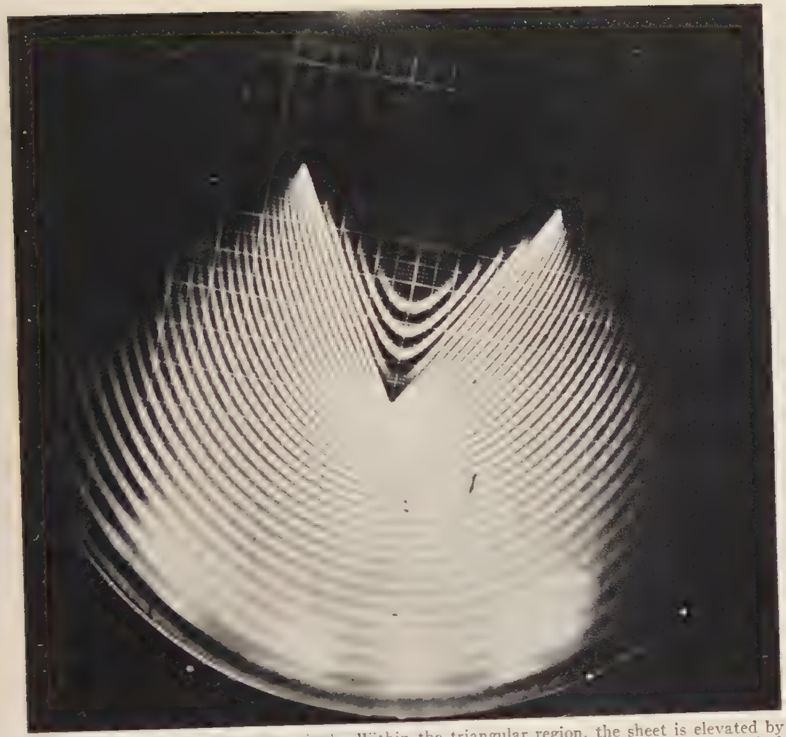

FIGURE 18. A model of a Poissonian field. Within the triangular region, the sheet is elevated by a uniform air pressure. Within this region, the contours represent the stress potential in a triangular shaft under torsion. The region external to the triangle represents the potential field between a triangular conductor and circular outer conductor.

interest. Like the fluid-mapper developed by A. D. Moore and described elsewhere in this monograph, the membrane analog provides a visual portrayal of the field. The vividness of this visual portrayal provides an important medium for performing mental experiments. Indeed, a person with experience is able to make qualitative analyses of potential problems in terms of the membrane configuration, using his imagination entirely. Further, the membrane analog has a high degree of flexibility in application. In such problems as design of an electrode configuration, the boundaries can be pushed around at will while the observer notes the resulting changes in the field. This feature is one which the membrane analog shares with the electrolytic tank, also described elsewhere in this monograph.

As to boundary conditions, known potential distributions are relatively easy to establish with a membrane, simply by supporting the membrane at the desired elevations. On the other hand, a distribution of known forces over the sheet is more difficult to establish on the membrane, but very easy to establish in the electrolytic tank. In the tank, the sources are electric currents which are easy to control in magnitude and easy to measure accurately.

Quantitatively, the membrane suffers generally in comparison with the electrolytic tank primarily because it is more difficult to measure elevations rapidly and accurately than it is to measure electrical potentials. When a high order of accuracy is not required, the membrane analog plus the contour-lighting technique provide a contour map of the potential field easily and rapidly.

I know of no way to simulate boundaries which are infinite in extent with a membrane analog, a procedure which presents no great difficulties in the electrolytic tank and is possible with the fluid mapper. Changes in the properties of the medium in which the potential field is established are easily handled in the tank, and they can be handled with the fluid mapper, but they are extremely difficult to achieve practically with a membrane analog. In the electrolytic tank, the depth of the conducting fluid may be made variable and, in the fluid mapper, the thickness of the flow space may be made variable, but specific variations of the thickness of a membrane would present difficulties great enough to warrant the use of another analog in this type of problem.

Conclusion

In summary, the membrane analog provides a vivid visual portrayal of a potential field in a uniform medium, and the contour-lighting technique makes it useful for rapid and quantitative measurements when a high degree of accuracy is not required. Its primary advantage is that it provides its user with what I like to call a *thinking tool* for performing mental experiments.

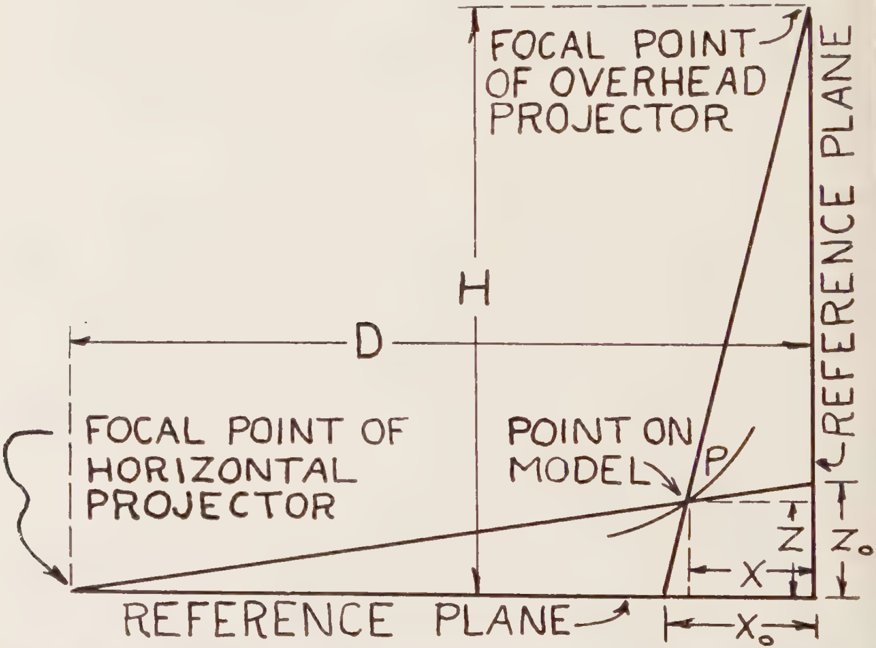
FOCAL POINT OF OVERHEAD PROJECTOR
REFERENCE PLANE
H
D
FOCAL POINT OF HORIZONTAL PROJECTOR
POINT ON MODEL
P
Z
Z₀
X
REFERENCE PLANE
X₀

FIGURE 19. Figure for analysis of the corrections required because the illuminating planes are not parallel but converge at the focal point of the lens. The analysis shows that the corrections are small when the dimensions of interest on the model are quite short with respect to the distance to the focal point of the projector.

APPENDIX

Analysis of Errors Due to the Tilting of the Illuminating Planes

The geometry of the tilted illuminating planes is shown in FIGURE 19. The contour projector is at the left, a distance D from the center of the rubber sheet. The coordinate projector is above the sheet, a distance H from the plane of the frame supporting the sheet. An elevated point P on the sheet is thus marked by the intersection of coordinate lines and contour lines x_0, y_0, z_0, where the subscript zero serves to distinguish the observed coordinates from the true coordinates, x, y, and z.

From the two sets of similar triangles, we can write

$$\frac{z_0 - z}{x} = \frac{z_0}{D} \tag{1}$$

and

$$\frac{x_0 - x}{z} = \frac{x_0}{H} \tag{2}$$

Similarly, for the coordinate perpendicular to the plane of FIGURE 19

$$\frac{y_0 - y}{z} = \frac{y_0}{H} \tag{3}$$

When these three equations are solved for the true coordinates in terms of the observed coordinates, the results are

$$z = z_0 \frac{1 - \dfrac{x_0}{D}}{1 - \dfrac{z_0 x_0}{HD}} \tag{4}$$

$$x = x_0 \left(1 - \frac{z}{H}\right) \tag{5}$$

To save the writing in EQUATION 5, z is given by the right hand side of EQUATION 4.

$$y = y_0 \left\{1 - \frac{z_0}{H}\left(1 - \frac{x}{D}\right)\right\} \tag{6}$$

To shorten the writing in EQUATION 6 also, x is given by the right-hand side of EQUATION 5.

To minimize the difference between the true coordinates and the observed coordinates, the horizontal projector should be located at a distance from the model which is considerably larger than the horizontal field of interest on the model. Similarly, the overhead projector should be located above the model at a distance which is considerably greater than the maximum elevation of the model. In a room in which the horizontal projector can be located 20 feet away from the model, the correction term is 5 per cent for points one foo away from the center or reference plane of the model. When the overhead projector is five feet above the reference plane, the horizontal correction is 1.6 per cent per inch of elevation of the sheet.

While the corrections required are independent of the focal length of the lens, the number of measuring increments, or contours per inch of elevation, does depend on the focal length. For this reason, lenses with quite long focal lengths give the best quantitative results.

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THE APPLICATION OF THE ELECTROLYTIC TANK TO THE SOLUTION OF POTENTIAL FIELD PROBLEMS

By Charles Hachemeister
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The electrolytic tank can be used to determine experimentally the solution of the Laplace equation with specified boundary conditions.[1, 2] It is especially useful when three-dimensional potential fields in homogeneous media are to be determined.

Utilization of the electrolytic tank is based on the analogy of steady electric fields in conductors to other potential fields such as electrostatic, magnetostatic, stationary temperature, fluid dynamic, and gravitational fields. In each case, a scalar potential can be used to define the field. When the region of interest is source-free, the scalar potential satisfies the Laplace differential equation, $\nabla^2\phi = 0$. (In some cases, as in magnetostatic and fluid dynamic fields, it may be necessary to introduce mathematical barrier surfaces in order that the scalar potential concept be retained.) The stream function is either the positive or the negative gradient of the potential, depending upon the sign conventionally adopted for the field.

The apparatus incorporates a large tank constructed of glass or of impregnated wood lined with metal and filled with distilled water to which an electrolyte such as copper sulphate has been added. Metal electrodes shaped to conform with the boundaries of the problem are immersed in the electrolyte. A probe is used to indicate the local potential.

The electric circuit is similar to a Wheatstone bridge (see FIGURE 1). The electrodes are connected to voltage sources which are adjusted to values proportioned to those of the problem. The probe is connected through a detection system to a reference voltage which may be obtained from a slide wire as shown in FIGURE 1. If moved so that no current ever flows through the detector, the probe traces an equipotential line. The position of the probe is mechanically transmitted to a stylus resting on a plotting board either by a pantograph or by a carriage system which allows free motion in two perpendicular directions.

FIGURE 2 shows an actual electrolytic tank system.

As previously stated, the field in the tank is analogous to other fields because of the satisfaction of the Laplace equation by steady current fields in homogeneous media. If steady potentials are used to excite the tank, polarization occurs in the electrolyte causing the medium to become heterogeneous and destroying the analogy upon which use of the apparatus is based. This difficulty is circumvented through the use of low-frequency alternating voltages.

FIGURE 3 shows a typical detector system. If the probe and reference voltages are equal, no signal appears at the input to the first stage of the tuned amplifiers; the current through the diodes of the last tube is zero and the milliammeter deflects to full scale. When the probe is not at the reference voltage, the difference is amplified and applied to the diodes, which then develop a bias

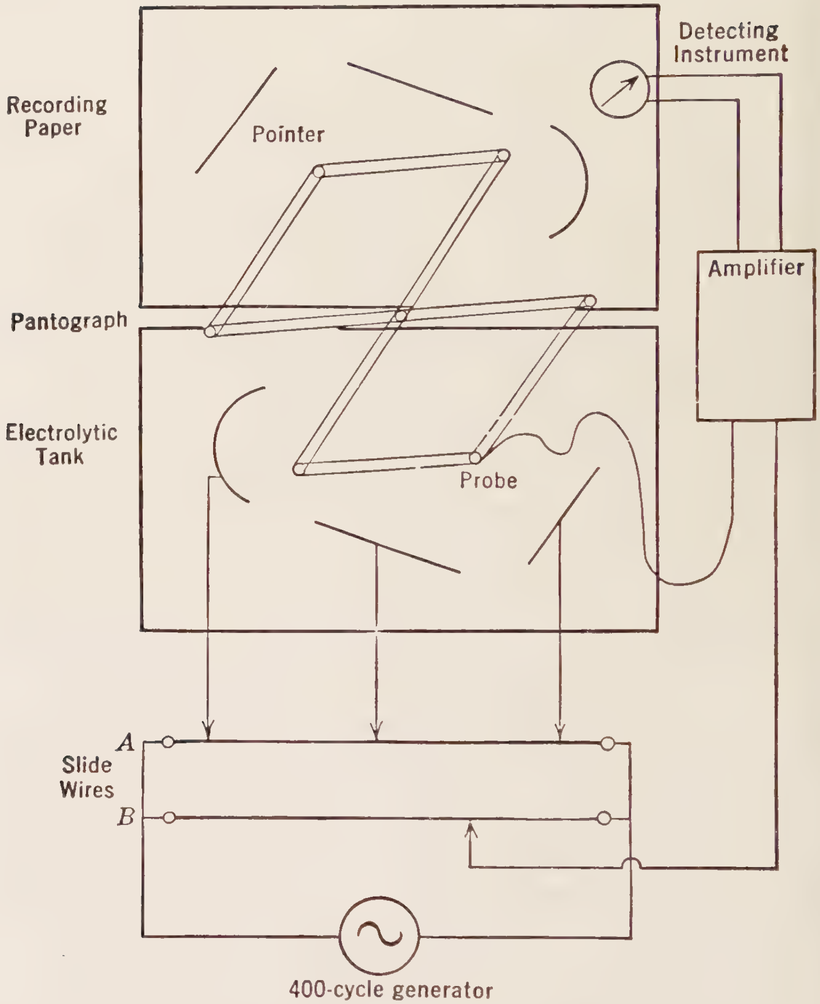


FIGURE 1. Diagram of electrolytic plotting tank (courtesy of John Wiley, New York, N. Y.).

on the last triode reducing the milliammeter indication. Thus, the null balance occurs at full scale of the milliammeter.

The frequency must be low enough so that, with the electrolyte used, the effects of the associated time-varying magnetic field can be neglected, and high enough so that the polarization effect during one-half cycle is negligible.

The probe construction and size must be such that disturbances of the field by the probe and the associated meniscus are tolerably small. There are two basic probe types, metal and liquid. The metal probe is a short thin needle of noncorroding metal protruding from a thin insulating tube through which is the connecting wire (FIGURE 3). The liquid probe consists of a small in-

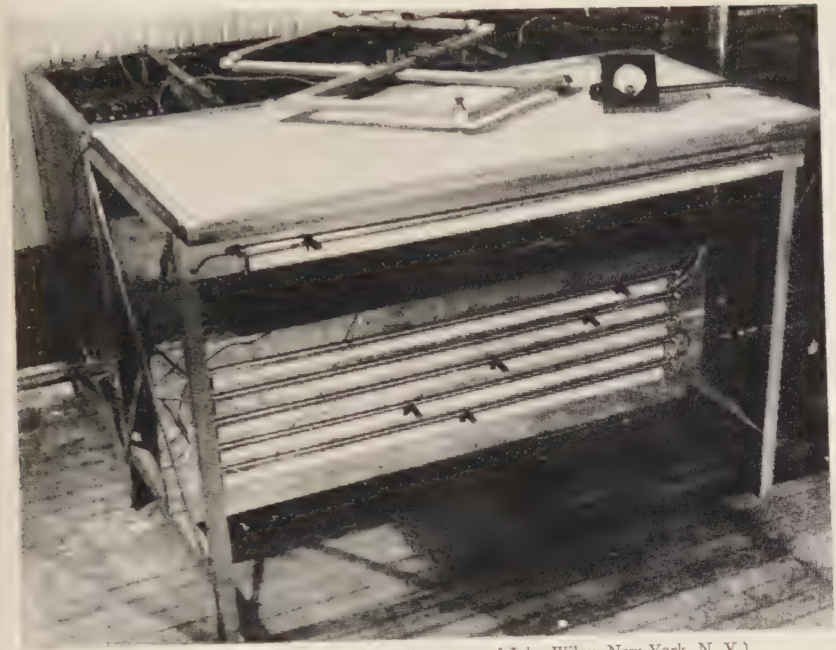


FIGURE 2. Electrolytic plotting tank (courtesy of John Wiley, New York, N. Y.).

sulating tube filled with electrolyte (FIGURE 4a). Such a probe has no polarization effects when placed in the electrolyte and, because of its smaller perturbing effect, size for size, larger diameters than metal probes can be used. A liquid surface probe (FIGURE 4b) consisting of an insulating plate, placed in the plane of the liquid surface, pierced with a small hole used as the capillary of the probe completely eliminates meniscus troubles.

The principle of operation of the tank is not so complex as to cause major problems to arise from it. The difficulties which arise are because of errors in the practical system. These errors can be divided into two principal classes, those resulting from failure of the tank to represent the field system it is desired to investigate, and those resulting from failure to measure the potentials in the tank with sufficient accuracy. The former class is due to the finite size of the tank and to polarization effects at the electrode surfaces. The latter class arises from perturbations of the field pattern caused by the insertion of measuring probes and from errors in the determination of the probe potentials.

As previously stated, polarization effects can be reduced by employing alternating instead of steady potentials. The remaining polarization effect, localized at the electrodes, is to produce, at the virtual boundary of an electrode and electrolyte, a potential different from that of the metal electrode. A judicious choice of electrode-electrolyte combination will further suppress but not eliminate this effect. For accurate results, it is necessary to measure the potential of the virtual interface. This measurement can be made by mount-

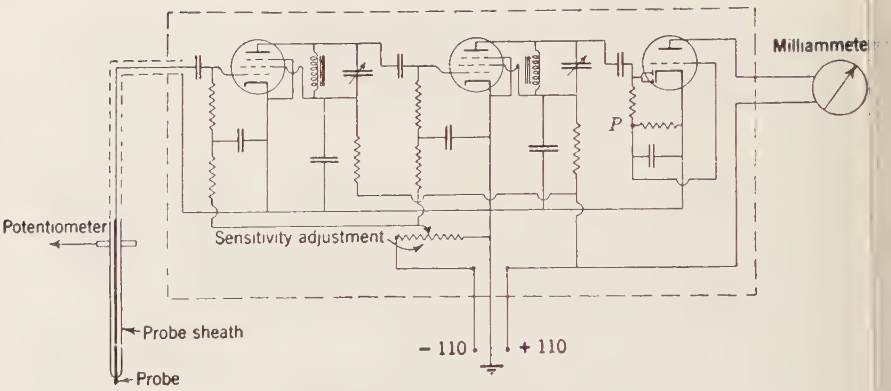


FIGURE 3. Circuit of Null-Reading instrument (courtesy of John Wiley, New York, N. Y.).

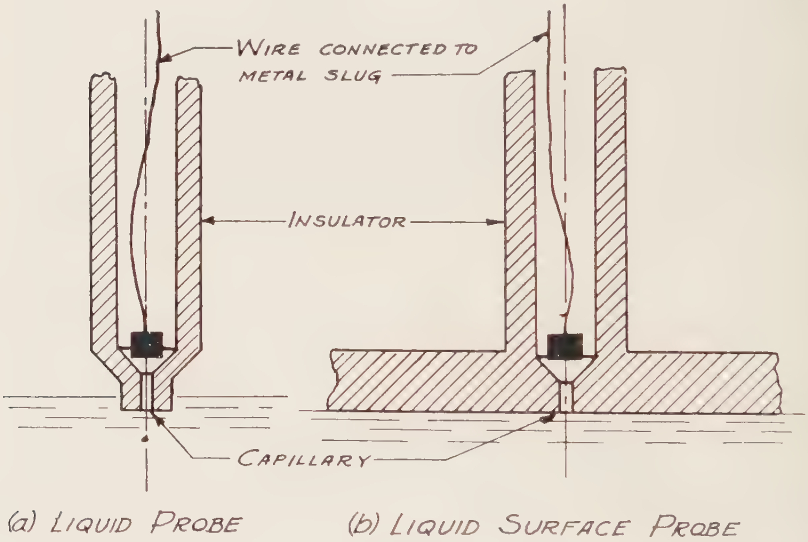


FIGURE 4.

ing within the electrode a liquid probe whose capillary is a hole pierced in the electrode surface.

The finite size of the tank limits the accuracy of the results associated with field problems, which are not locally bounded. In order to simulate the actual field, it may be necessary to proportion the electrode sizes and locations so that the walls of the tank are electrically far from the sources of the field. Nonconducting walls are preferable when studies are made of "unbounded" fields. Often it is possible to use one or more tank walls as planes of symmetry and so virtually increase the size of the tank.

Errors attributable to the probes and their associated circuit cannot be eliminated. They stem primarily from polarization around metal probes, meniscus effects which locally distort the electrolyte surface, and the anomaly effect caused by the introduction of the probe into an otherwise homogeneous electrolyte.

Polarization at metal probes can be suppressed through the choice of the metal, the use of a null method for measuring the probe potential, and by proportioning the metal so that the current flowing laterally through it is small. The meniscus and anomaly effects can be reduced only through careful design of the probes. The liquid surface probe, previously described, does not suffer from these latter faults but is too bulky for general explorations.

Refinements of the potential measuring system include the use of square wave excitation and comparator amplifiers.[6]

The positioning of the electrodes is dictated by the field to be studied. For two-dimensional fields, it is usually best to let the plane of the field coincide with the surface of the electrolyte, and allow the electrode structures to rest on the floor of the tank, which should be coated with insulating cement. The current flow will then retain its two-dimensional character.

FIGURE 5 shows an arrangement for the study of the effect of a rectangular shield around a two-wire transmission line. The electrical circuit allows studies of balanced and unbalanced lines.

Of the three-dimensional fields, those having axial symmetry are the simplest to measure because a plot in any meridian plane suffices to define the field

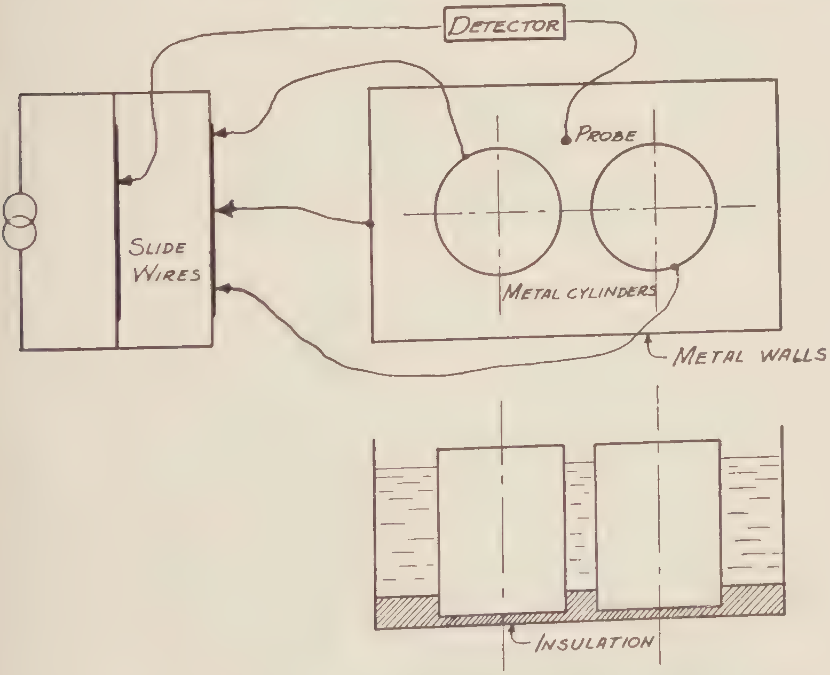
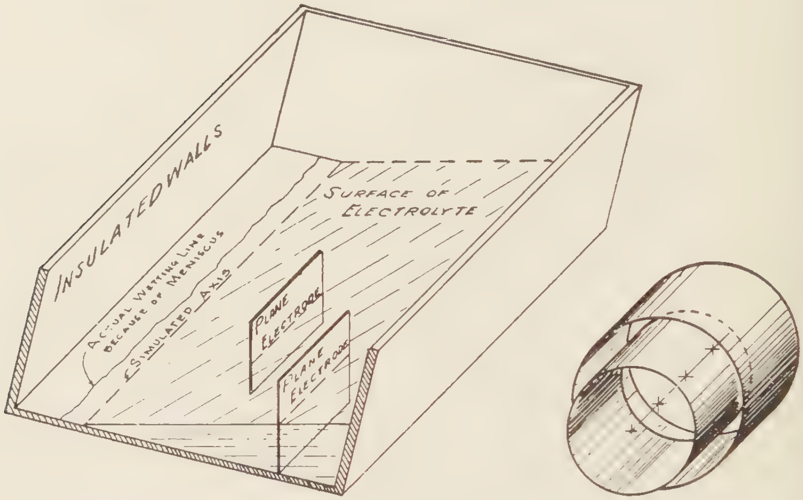


FIGURE 5. Circuit and electrode arrangement for the study of the field of a transmission line within a rectangular shield.



(a) WEDGE TANK AND ELECTRODES FOR THE STUDY OF THE FIELD OF TWO COAXIAL CYLINDERS. (b) ELECTRODES OF ACTUAL FIELD.

FIGURE 6. Tilted tank forms a wedge of electrolyte.

completely. If knowledge of the field near the axis is not important, a wedge-shaped trough can be used. The floor of the tank, or an insulating plate, is made to coincide with one meridian section and the liquid surface with another. The wetting line on the tank floor then is the axis of symmetry, and electrodes are located relative to it. If the wedge angle is made sufficiently small, it is not necessary to curve the electrodes to correspond with the axial symmetry. Thus, it is possible to examine the fields associated with nondevelopable electrode surfaces, avoiding the difficulty of forming doubly curved electrodes. FIGURE 6 shows the arrangement for studying the field of coaxial cylinders.

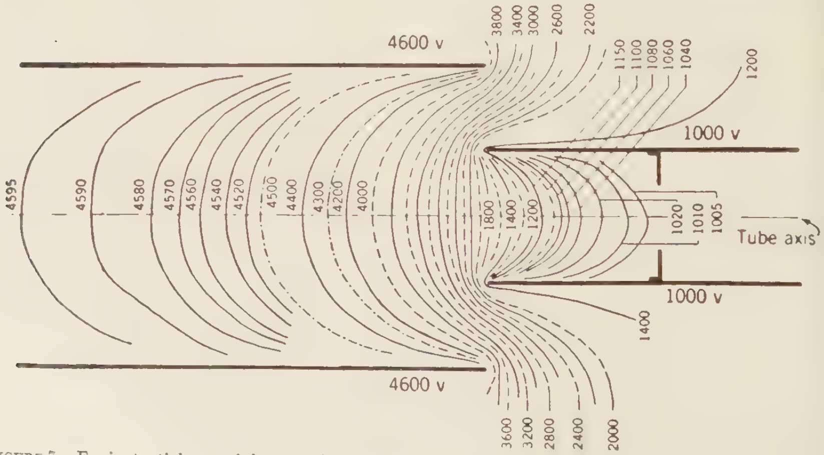


FIGURE 7. Equipotential map of the second lens of an electron gun (courtesy of John Wiley, New York, N. Y.).

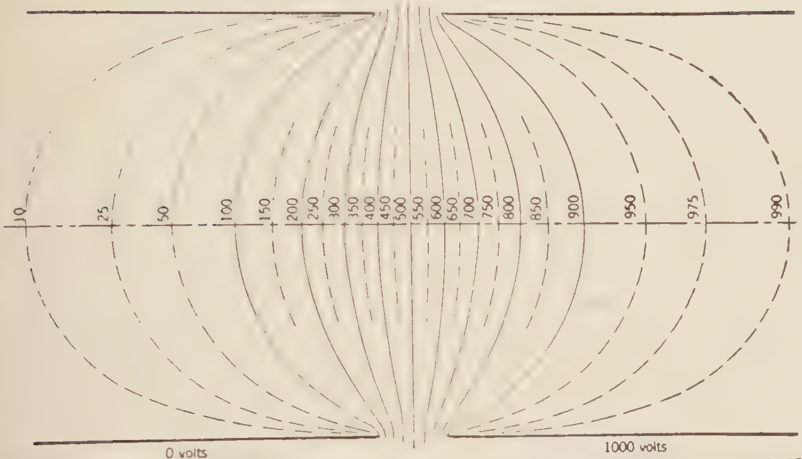
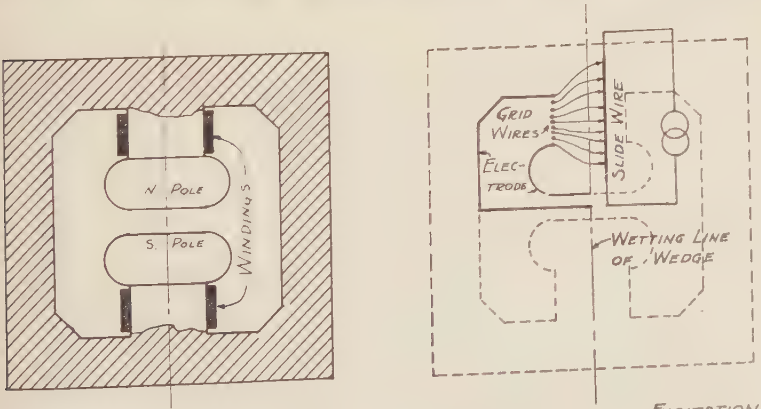


FIGURE 8. Equipotential map of an equidiameter cylinder lens (courtesy of John Wiley, New York, N. Y.).

Results near the axis are not reliable because of meniscus effects associated with both the bottom of the tank and with the probe. The axis can be virtually approached through the use of very large models so that a tolerable probe-to-axis spacing represents a very small distance in the actual structure. Only if semielectrodes are used can readings be taken on the axis. FIGURES 7 and 8 show potential maps obtained using semielectrodes in the tank of FIGURE 2.

The construction of electrodes and the method of applying the potentials require more ingenuity when the actual field is magnetic.[3, 5] In such fields, the applied magnetostatic potential is usually distributed throughout the coil windings and, unless an iron structure is used, there are few, if any, surfaces known to be equipotentials. Although not exactly so, an iron surface can be



(a) MERIDIAN SECTION OF ACTUAL MAGNETIC STRUCTURE.

(b) ELECTRODES AND EXCITATION FOR USE IN A WEDGE ELECTROLYTE

FIGURE 9. Arrangement for a magnetic problem.

assumed to be equipotential. FIGURE 9 shows the electrode and excitation arrangement for determining the field within an ironclad electromagnet. I is assumed that the coils can be replaced by current sheets, and the increase of magnetostatic potential is linear throughout the axial length of the coil. The permeability of the iron is sufficiently high, so that the iron-air boundaries are essentially equipotentials. Axial and central cross-sectional symmetries are exploited, so that, with the use of a wedge tank, flat metal strips, bent as indicated in FIGURE 9b, suffice to define the boundaries. Small grid wires, equally spaced and at successive increments of potential, simulate the coil in the actual structure.

The value and direction of the stream function can be determined within reasonable accuracy through the use of a cluster of four probes, as shown in FIGURE 10. The potential difference between the *a* and *b* probes divided by the small spacing, *s*, is the vertical component of the electric field. Probes 1 and 2 yield the horizontal component. The increased perturbation of the field and the practical difficulties of measuring simultaneously four potentials which differ by only small amounts make the results less reliable than those obtained with a single probe.

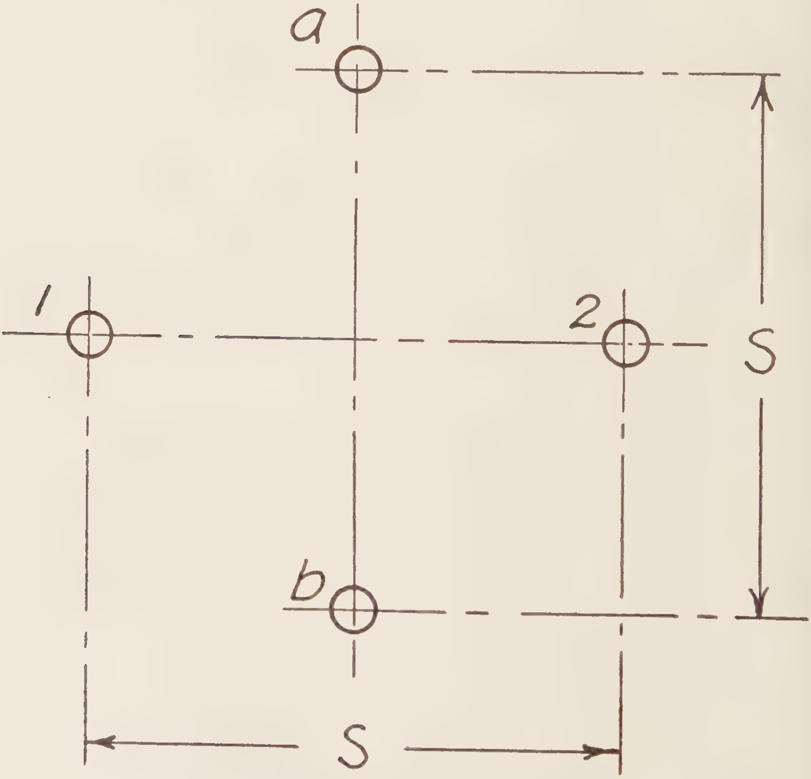


FIGURE 10. Four-probe cluster for measuring the electric field.

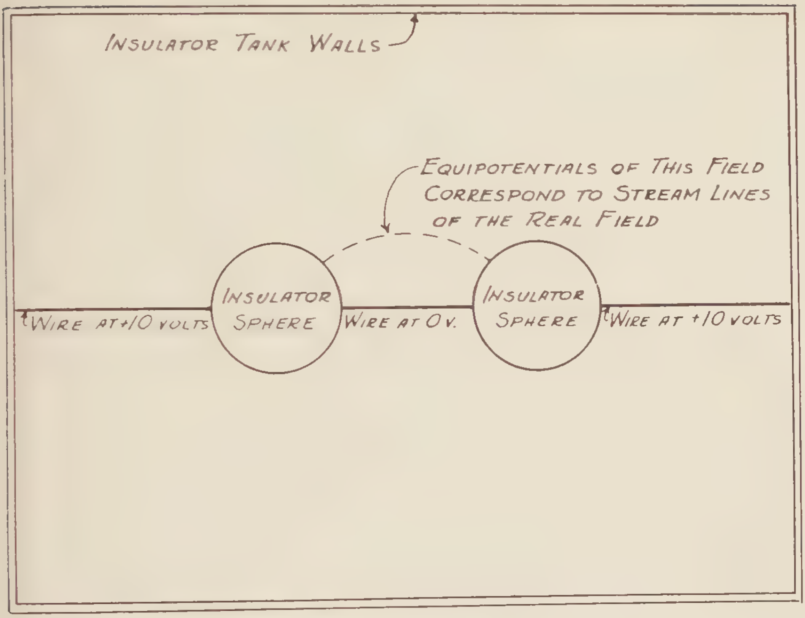
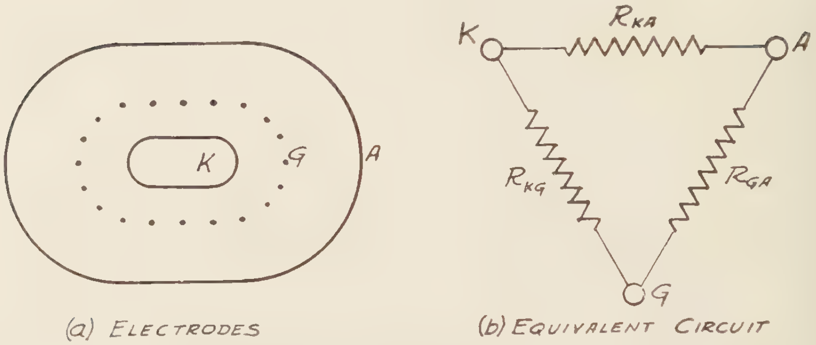


FIGURE 11. Electrodes and insulators for finding the stream lines of two metal spheres charged equally and opposite.

If only the streamlines are of interest, they can be sketched orthogonally with equipotentials. In some cases, it is feasible to plot the streamlines directly. The technique is based upon the orthogonality of the streamlines with the equipotentials. Wire electrodes bent to correspond with the walls of thin flux tubes are positioned in the electrolyte to correspond with the flux tube walls. Those volumes of the electrolyte bounded by equipotentials of the real field are displaced by insulators. The resulting equipotential surfaces then coincide with flux tube walls of the real field. FIGURE 11 shows the electrode and insulator arrangement for mapping the field lines of two large spheres carrying equal and opposite charges. Because of meniscus troubles, it is better to immerse the spheres well into the electrolyte and use a deep probe to explore the field. FIGURE 11 represents a parallel wire transmission line, if the circles represent cylinders and the lines, planes.

Systems for automatically plotting of the field have been constructed.[4, 7] They operate on the principle of servo mechanisms moving the probe so that it follows an equipotential. Description of such systems would take more space than can be allotted in this paper.

The measurement technique is greatly simplified if the field configuration is of no interest, but self coefficients and mutual coefficients of the electrode array are desired. It then suffices to measure the resistance between sets of electrodes in the tank and apply the appropriate conversion formula. FIGURE 12 shows the equivalent circuit and the electrode arrangement corresponding



(a) Electrodes (b) Equivalent Circuit

FIGURE 12. Arrangement for determining the mutual capacitances of a triode vacuum tube.

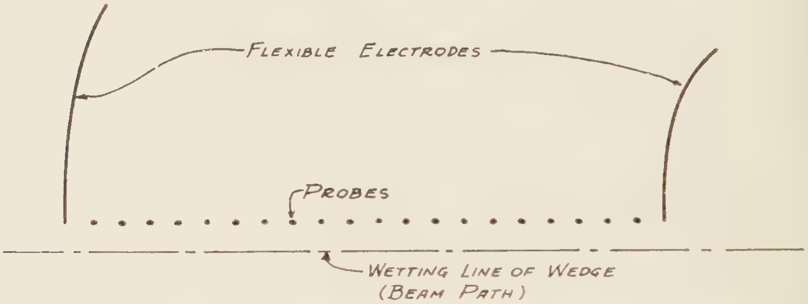


FIGURE 13. Arrangement for determining electrode shapes for confining an electron beam.

to a cylindrical triode with axially directed grid wires which are connected together above the electrolyte surface.

The values of the measured resistances between each of the three pairs of terminals A, K, and G are sufficient to calculate the mutual resistances R_{KG}, R_{KA}, R_{GA}. The mutual capacitances can then be calculated using $C = pe/R$ where ρ is the resistivity of the electrolyte and ϵ the permittivity of the medium in the triodo (free space).

Another application of the tank is the design of electrode shapes to produce a required potential distribution. One of the problems so solved was that of producing an electrostatic field which would confine an electron beam so it would not spread because of the mutual repulsion of the electrons. The necessary distribution along the beam can be analytically determined.

A set of probes and deformable electrodes was arranged in a wedge tank as shown in FIGURE 13. The reference voltage for each probe was adjusted to the value calculated for its location and the electrodes formed so that each probe detector indicated a null.

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FLUID MAPPERS AS VISUAL ANALOGS FOR POTENTIAL FIELDS

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(1) *Introduction*

In a fluid mapper, streamline fluid flow is made to occur in a thin flow space between an upper and a lower member. The upper member is a flat piece of plate glass, called the plate. The lower member may be a slab of suitable material, usually plaster, or the surface of a "sandbed," or a combination of the two. The photographs reproduced herewith represent all three types. The fluid typically used is water. Normally, the two members are operated totally immersed in a tray of the operating fluid.

When a given potential field situation is to be portrayed, the lower member of the fluid mapper is built to scale, with suitable boundaries, open or closed; islands, if any; one or more sources or sinks; and so on. Each source or sink is connected by a rubber tube to a tank, so that raising or lowering a tank will induce flow in the flow space. When the operation is conducted so that the flow is not affected by inertia, the flow pattern set up can quite accurately duplicate either the equipotential lines, or else the flux lines, of the potential field under consideration.

Visible flow lines are produced, typically, by the use of potassium permanganate crystals. If the crystals are sprinkled onto the lower member prior to placing the plate, their dye lines move along the floor of the flow and form a floor pattern, as in FIGURES 1, 4, and 5. If attached to the plate, a sharper set of lines is often obtained: the dye lines form a ceiling pattern at first, then sink slightly to be carried along at the higher velocities of lower levels in the flow space. Ceiling patterns are seen in FIGURES 2, 3, 6, and 7.

The writer invented the sandbed type of fluid flow analog in 1943, and proved it experimentally. That was the beginning of the modern work with the fluid flow analog. In 1948, the writer began the development of plaster techniques, and the devising of numerous forms of what the writer has called fluid mappers followed in rapid succession. Five papers (see references) have been published. Since these papers present many of the techniques and show many of the things that can be done with fluid mappers, the present paper will not attempt to include the details already published.

(2) *The Analog*

Going across the thin flow space vertically, the velocity distribution is parabolic. This particular phenomenon has no counterpart in any of the potential fields being simulated. In this respect, therefore, the fluid flow situation is not an analog for the potential field situation. But if visible dye-line patterns are formed at the floor and the ceiling of the flow, and at levels in between, it is found that all these patterns coincide when viewed from directly overhead. Professor Hele-Shaw[1, 2] in England, through his beautiful pioneering work, showed experimentally and analytically that the flow patterns

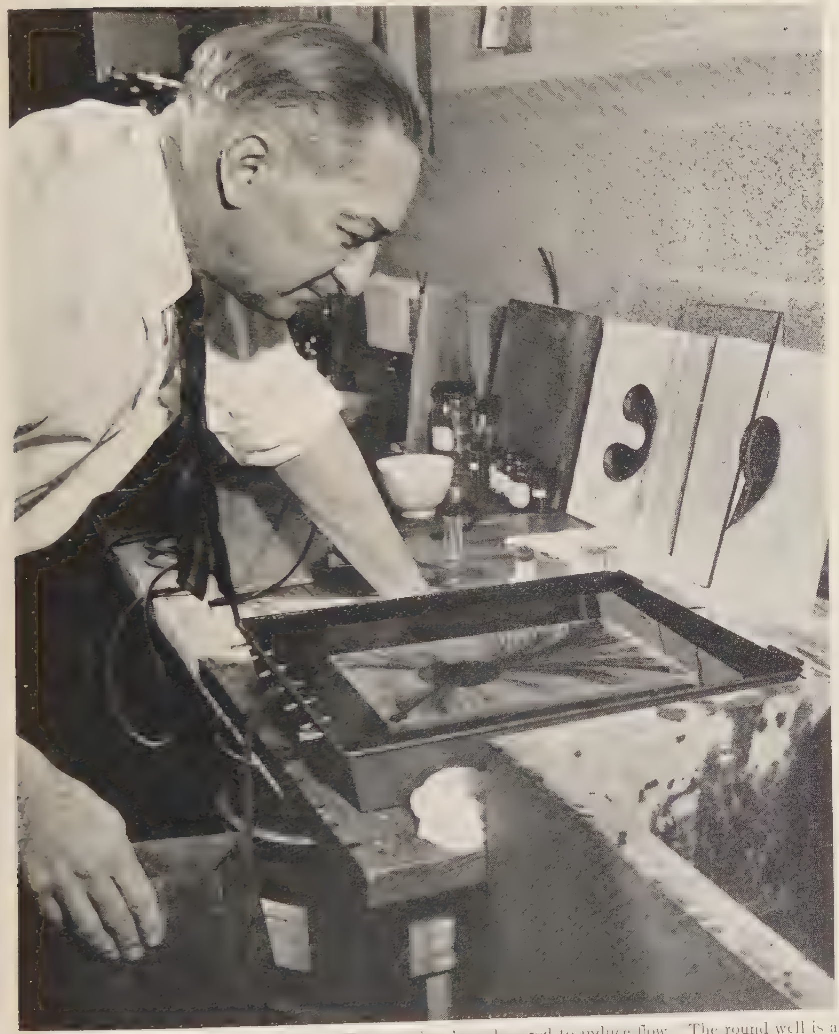

FIGURE 1. Fluid mapper in operation. The tank has been lowered to induce flow. The round well is acting as a sink.

thus set up do simulate the lines of the corresponding potential field. His work was done a half-century ago. His techniques, though admirable for their accuracy, were costly and inflexible, which may account for the fact that his work was not developed.

(3) *Slabs*

A slab, as shown in FIGURE 2, in theory, may be made of any suitable material. For demonstration purposes, however, and for many actual applications,

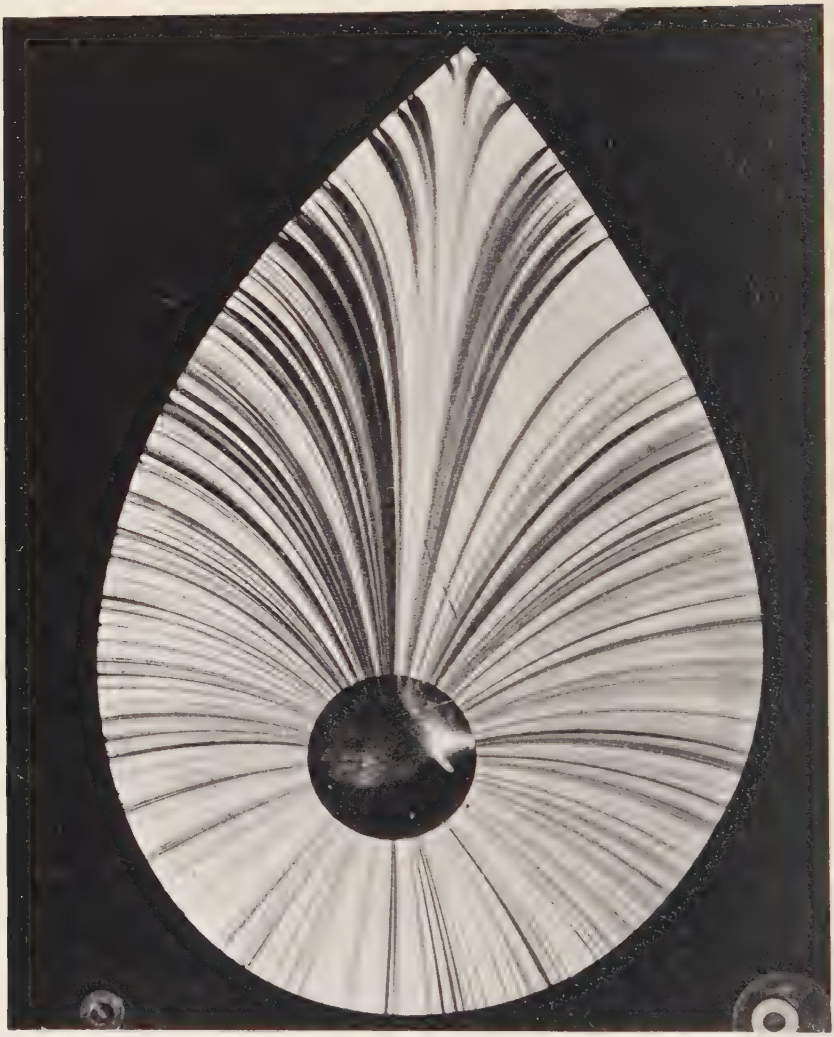

FIGURE 2. Fluid mapper with ceiling pattern. Crystals invisible here) are attached to plate, just outside of outer boundary. The round well is acting as a sink.

plaster is by long odds the material of choice. By using techniques worked out by the writer, plaster slabs can be cast on plate glass to get a flat surface; plaster feet can be added; and plaster techniques can be used for finishing well bottoms and attaching the tubes to the wells at the same time. Thus, plaster is a cheap material of great adaptability.

Patching plaster can be, and has been used. Plaster of Paris may also be used, but the best plaster, as to setting time, strength, density, and accuracy, is a product that dentists call dental stone. Being mainly calcium sulfate, it is admittedly slightly soluble in water. For brief operations with water as the

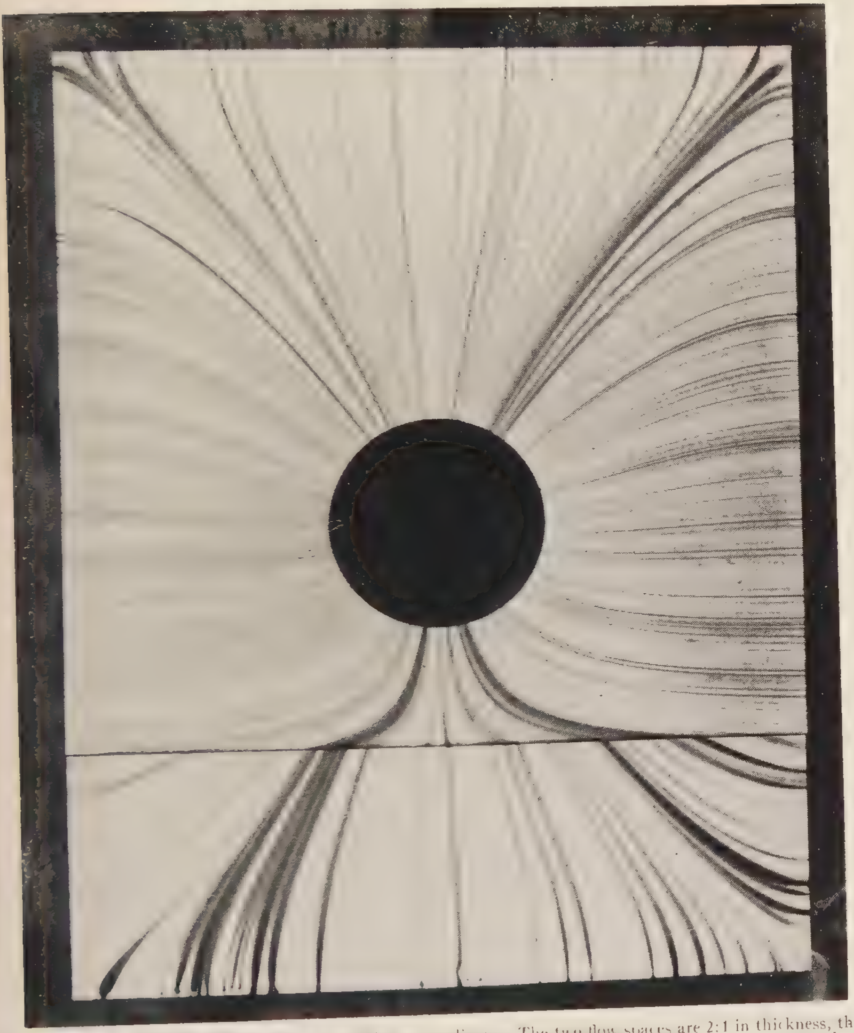

FIGURE 3. Fluid mapper simulating a field in two mediums. The two flow spaces are 2:1 in thickness, thus representing an 8:1 ratio for the dielectric constants, thermal conductivities, etc. Refraction exhibited. A ceiling pattern. The well is a sink.

fluid, however, no trouble is encountered. For longer operations, erosion of the surface due to its going into solution can be almost stopped by first saturating the water with calcium sulfate.

Time and again, during a class demonstration, the writer has cast and finished a simple type of slab and had it in operation within a period of one hour. The presentation of this paper at the conference on which this monograph is based was accompanied by a lecture-demonstration in which a slab was made and operated, from start to finish. This showed the ease and certainty with

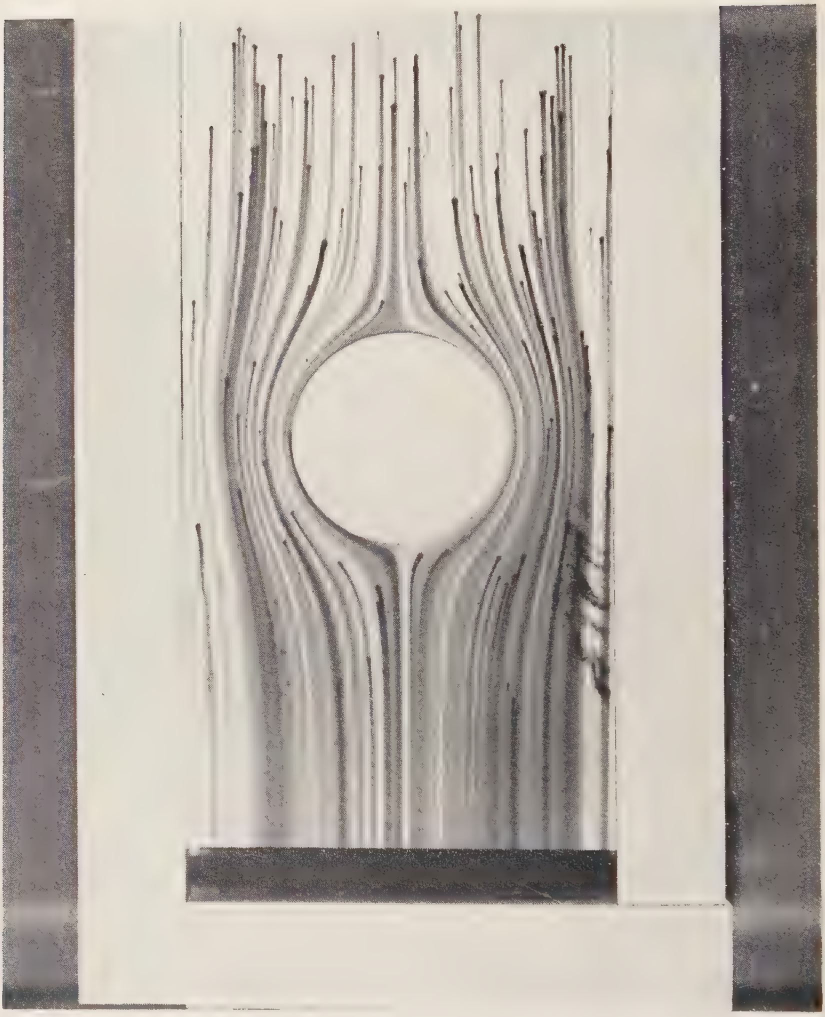

FIGURE 4. Plaster slab with plaster barriers and plaster island. The crystals rest on the slab, forming a floor pattern.

which plaster techniques can bring the simpler slabs into existence. More intricate slabs will, of course, take more time.

Although the slab of FIGURE 3 shows an intricate pattern, the slab itself was easily made. It was cast in two pieces, the two parts then being joined at the bottom surface by added plaster. The two parts are offset as to upper surfaces, thereby giving the larger area a flow space that is twice that of the smaller area. Owing to a spacing-cubed law[3] that prevails, we cube the 2:1 ratio and get 8:1. This result means we are here simulating a two-medium field and showing the refraction phenomena. For example, if two-dimensional

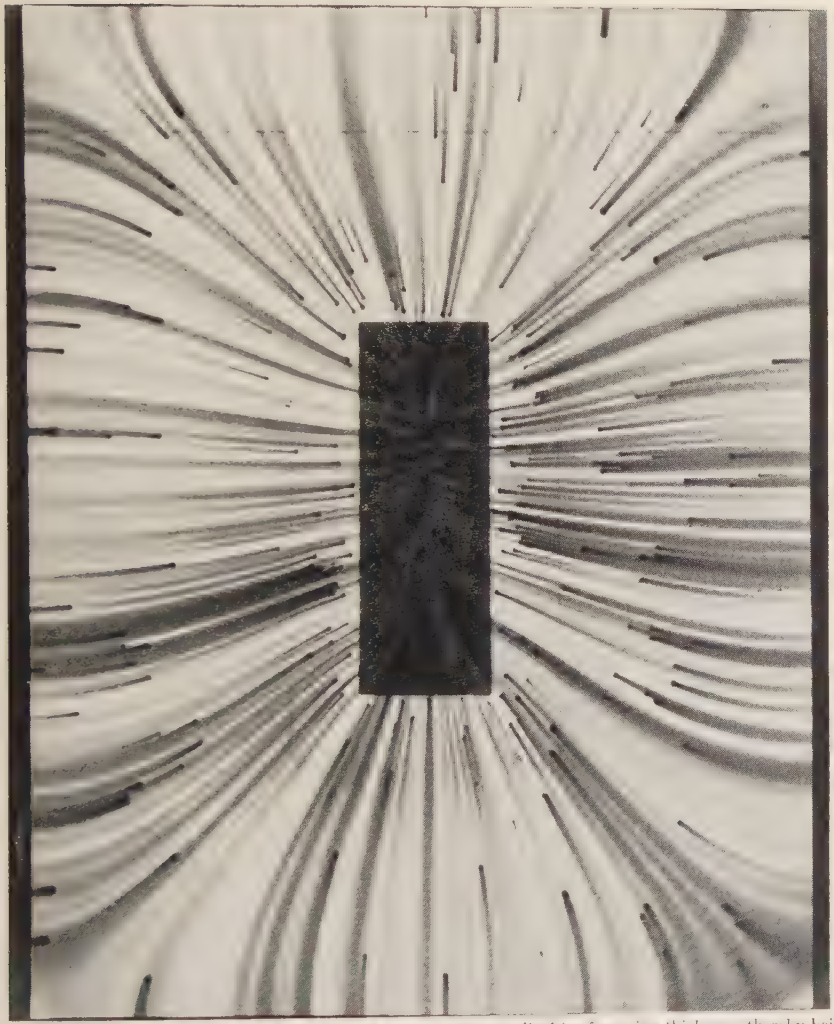

FIGURE 5. Slab with sandbed as a distributed source. This sandbed is of varying thickness, thereby being a distributed source of nonuniform character. Over the sandbed, Poisson's equation prevails, over the slab, Laplace's equation

heat conduction is being simulated, then the thermal conductivities represented are in the ratio of 8:1.

Flow around an "island" is shown in FIGURE 4. The slab itself was made of four plaster castings, held together with added plaster. The large central casting is depressed to form the flow space. The plate rests upon the narrow white parts, these parts forming the barriers. The round island is a thin casting made between two pieces of plate glass by a "squeeze-out" technique, and later trimmed to roundness. It is as thick as the flow space. It rests upon

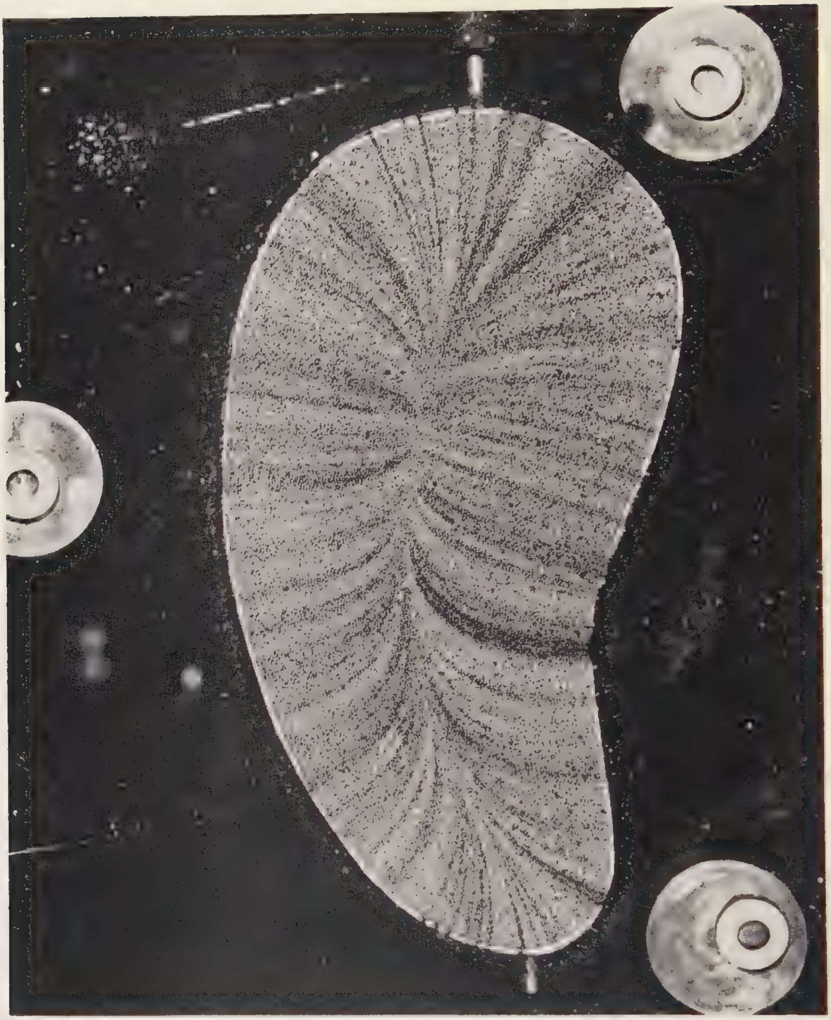

Figure 6. Isolated, irregular sandbed acting as a uniform sink Boundary is an isopressure line. Interpreted as a uniformly distributed heat source, the boundary is an isotherm; the kernel is the hot spot; flow lines delineate heat flow lines

the slab, and the plate rests upon it as well as on the barriers. With some simple adjustable mold pieces for making rectangular slabs, anyone can soon learn to make a fluid mapper like the one shown in figure 4 and put it into operation.

(4) *Flow Spacings*

The thickness of flow space is not a critical matter. Most of the writer's fluid mappers have been operated with a spacing of about 30 to 40 mils. Theoretically, there is no lower limit of flow spacing, provided accuracy is main-

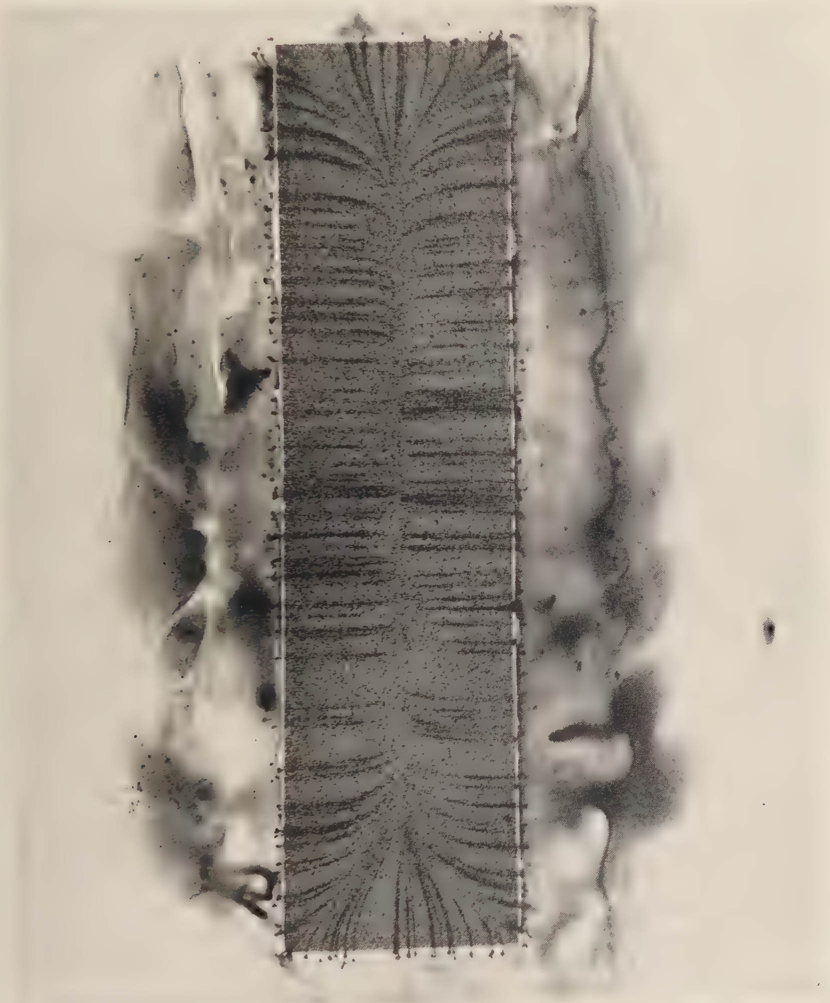

FIGURE 7. Isolated rectangular sandbed acting as a uniform distributed sink. The boundary is an isopressure line.

tained. The upper limit in any particular mapper is reached when flow patterns at different levels no longer agree, and wandering of fluid occurs. No one has been able to work out the upper limit on a theoretical basis; probably, it cannot be done. But experimentation with a specific mapper will determine it, for that mapper, and for the fluid chosen and the velocities used.

Within the wide range of spacings available, one can make a nice demonstration by operating with some value of spacing, and observing the pattern, then doubling the flow space, and operating again. If the upper limit has not been exceeded, the two patterns will be identical.

(5) *Fluid Mappers with Ordinary Sources*

The fluid mappers of FIGURES 1 to 4 inclusive may all be classified together, in that they all represent "ordinary" two-dimensional potential fields that satisfy Laplace's Equation. Such fields can be represented by two orthogonal sets of lines: two sets of lines, usually curved, that are everywhere at a right angle to each other at their intersections. Using the broadest terminology to cover all such fields, one of the sets of lines is called the equipotential lines. The other set is called flux lines. More specialized names are often used for particular phenomena. If two flux lines are used to delineate a tube of flux, it is an ordinary tube: the flux does not change as we go along the tube. The fluid mappers mentioned above represent such fields, in that if we let two dye lines delineate a flow tube, it will be an ordinary or unaugmented tube. All the fluid entering one end of the tube may be found anywhere along it, and will all depart at the other end.

In FIGURE 2, for example, we see but one set of lines, the flow lines. But we ourselves could carefully draw in the orthogonal system, and then both sets would be available. Which of these would really represent flux, and which potential, would depend on the actual phenomenon being simulated. Three examples will bring out this point (we continue to refer to FIGURE 2):

First, if the fluid mapper is thought of as simulating heat flow in a solid, then the fluid flow lines represent heat flow or flux, and the orthogonal lines represent isothermal (equipotential) lines;

Second, and likewise, if it represents an electrostatic field, the flow lines again represent flux lines, and the orthogonal lines stand for equipotential lines;

But third, if the slab represents iron of high but uniform permeability, and a conductor through the hole has a current which sets up a magnetic field in the iron, then the flow lines represent equipotentials, and the orthogonal lines represent flux lines.

The writer is frequently asked, "Why not build two fluid mappers, each to yield one of the two orthogonal sets of lines of a given case?" Generally speaking, and with rare exceptions, this is impossible. What can be done, if one insists on doing it, is first to make the mapper, which is possible, operate it, and get its pattern on record. From that, a second mapper can be built which will portray some part of (sometimes most of) the orthogonal system. Actually, as far as the writer knows, all field analogs are inherently subject to this same limitation.

Instead of trying to make an analog yield both sets of lines, it is nearly always (and perhaps always) easier to get one set of lines from the analog, and then add the other set by appropriate graphical procedures.[3, 7]

(6) *The Sandbed*

In FIGURE 2, we have an ordinary well, the edge of which acts as an isopressure line. The well is here acting as a sink. The flow lines leave the outer isopressure boundary orthogonally, and arrive at the well boundary orthogonally. The flow may be reversed, to yield the same pattern.

If the slab in FIGURE 5 had an ordinary well, with the well acting as a source, then, again, the flow lines would leave its boundary orthogonally. But this is no ordinary well. It is a "sandbed."[3, 4] A fine screen has been put across the bottom of this well. A plenum chamber has been built beneath the screen, with the tube connected to it. The plenum chamber is deep enough so that pressure drops in the chamber may be ignored. We have then filled in above the screen with sand or any other suitable material, leveling the sandbed off to the plane of the slab surface. If the "sand" is fine enough, and if the sandbed depth is great enough, the pressure drop up through the sandbed is so great that, essentially, the flow up through the sandbed ignores the fact that slight differences of pressure exist in the flow space above the sandbed. If the sandbed is of uniform thickness, as it is in FIGURES 6 and 7, then the fluid is forced to appear or disappear uniformly at the top of the sandbed. In FIGURE 5, the bottom of the well and its screen are sloped, so that the sandbed thickness is three times as great at one end as at the other. The thin part of the bed is nearest to where the kernel, or apparent center of flow, is located.

(7) *Sandbed Material*

For his first sandbeds, built in 1943, the writer actually used sand; hence, the name. Sand is quite usable, except for the troublesome fact that it is so light in weight that it is too easily disturbed. After World War II, when other materials became generally available again, metallic "shot" was settled upon as the material of choice. Metallic particles[6] of nickel, copper, *etc.*, are available. The granules that seem to work best are usually about 14 to 20 mils in diameter.

(8) *The Distributed Source*

The sandbed analog is perhaps most easily explained in terms of heat production and conduction. Imagine that, in FIGURE 5, the entire slab represents the rectangular cross section of a long piece of heat-conducting material having uniform thermal conductivity throughout. Let heat be generated or produced in some manner throughout that central part of the solid which is represented by the sandbed. Then the heat would have no choice but to start from that place where some of it is produced, and proceed to flow somewhere. If the entire outer surface of the large piece is maintained as an isotherm, then the heat would have to obey the physical laws of conduction, arrange itself in some pattern of flow, and all arrive orthogonally at the outer boundary.

In the sandbed fluid mapper built to simulate such a case, the fluid is forced to appear in the flow space over the sandbed, and it then has no choice but to flow, by corresponding physical laws, to the open boundary of the slab. By using appropriate sandbed depths here and there, the rate of appearance of fluid over the sandbed is made to copy the distribution of heat production; then the fluid mapper pattern will simulate the actual heat-flow lines.

Distributed-source phenomena occur when heat production is distributed throughout part or all of a volume; when space charges set up electrostatic fields; when coil cross sections set up magnetic fields; and in other situations. The field within a distributed source is not the ordinary kind which satisfies Laplace's equation; instead, Poisson's equation prevails. The flux or flow tubes are not "ordinary," with a constancy of flux or flow; instead, we have augmented tubes of flow. The flux or flow increases or decreases, as we follow along a tube.

Until very recently, the world literature offered very few drawings, pictures, or other visual representations of distributed-source field situations. There were three reasons for this scarcity. First, only a very few such fields are simple enough to yield to mathematical attack. Second, these fields are so complex that the attempt to produce even rough sketches of what goes on is often quite beyond the degree of insight available to the human mind. Third, there has been no analog available that could relatively easily portray these situations in visual form. With the advent of the sandbed fluid mapper, this lack is being rectified.

(9) *Some Properties of Distributed-Source Fields*

Fields due to distributed sources are so difficult to think about and work with, and adequate visual portrayals have been so scarce, that even those who deal considerably with field theory and field problems are often quite unfamiliar with them. The writer has had an unparalleled opportunity to learn this fact in showing sandbed fluid mapper slides while giving about 56 fluid mapper lecture-demonstrations throughout the country to scientific and engineering groups in colleges, industries, and research units. Four misconceptions or wrong expectations are so commonly entertained that they should be mentioned.

First, those who look at a distributed-source field such as is seen in FIGURE 5 are often prone to think that the kernel is the place where all of the flux or flow originates. This thought is an illusion. Admittedly, it does look that way. Actually, of course, flow tubes starting at the kernel have their flows augmented as they cross the sandbed. In other words, fluid is appearing all over the sandbed, and has to flow from where it does originate. The kernel itself, in a heat-flow case, is the hot spot; or, in a space charge, is the point of high or low potential.

Second, many investigators are surprised to find that the flux or flow is not orthogonal to the boundary of the distributed source. It will be, as in FIGURES 6 and 7, if that boundary is an equipotential line. But in FIGURE 5 this boundary is not an equipotential, and the flow, as shown, crosses it in whatever fashion is called for by the case.

Third, it is commonly expected that, in crossing the source boundary, as in FIGURE 5, refraction will occur. There is no refraction here, provided, as in this case, that the medium is the same throughout. What is present, is a change of curvature. There will be refraction when the distributed source occurs in one medium, and the surrounding field has another medium. For example, if the slab part of FIGURE 5 were to represent the thick wall of a steel tube, and the sandbed part stood for a filling of nuclear reacting material producing heat, these two materials having different thermal conductivities, then the heat-flow lines would be refracted at the interface. Correspondingly, the sandbed mapper would then be made up with a sandbed surface above or below that of the slab. It would be a two-space job, representing two media, and the flow lines would, of course, show refraction.

Fourth, if some change is made that is going to shift the position of the kernel, there is a strong tendency on the part of about two out of three observers to predict a movement in the wrong direction. This tendency alone shows how difficult it is to have a true insight into these fields until the mind is trained by seeing a number of cases, and by learning what the factors really are which influence the change to a new conformation.

(10) *Isolated Sandbeds*

When a fluid mapper's flow space is confined entirely to the area over a sandbed, the sandbed is isolated—there is no slab surrounding it. The edge or boundary of the sandbed, being open to tray water, is then an isopressure line; the flow lines are orthogonal to the boundary (see FIGURES 6 and 7). The field is all Poissonian, being entirely within the distributed source.

The irregular sandbed of FIGURE 6 has a definite kernel location, whereas the rectangular sandbed of FIGURE 7 is so elongated that, in effect, the kernal appears to be elongated, becoming a line along the major axis.

FIGURE 6 shows one of the writer's earlier jobs, all-metal except for having a plaster bottom. A great deal of time went into forming a brass strip into a ring, soldering brass rods across it to support a screen, and then fitting a screen onto it to support the sandbed. The sandbed occupies the upper half, and the plenum chamber the lower half.

FIGURE 7 shows a later design, using plaster techniques. Omitting details, be it said that, with plaster rather than with soldering methods, construction is much simpler and easier. The plaster that is seen here, surrounding the sandbed, is wholly constructional. It is depressed considerably below the lip of the sandbed well, permitting the sandbed boundary to operate as an isopressure line. That is, the presence of the plaster, in this mapper, has nothing to do with the pattern over the sandbed.

(11) *The Isolated Sandbed as an Analog*

The isolated sandbed is an analog for a number of distributed field phenomena, some of which will be mentioned. Referring to FIGURE 6, if heat-conducting and heat-producing material is uniformly packed into a thin-walled tube, and the tube is maintained as an isotherm, the fluid mapper flow lines duplicate the heat flow lines. If the tube, next, is empty, except for containing a uniform space charge, the flow lines show the electrostatic field conformation. Next, let us remove the filling from the sandbed, put a soap film across the top of the well, and inflate it slightly: the films' contour lines would be orthogonal to the sandbed mapper's flow lines.[4] The sandbed is accordingly an analog for the soap film, which, in turn, can be used for solving for torsional stresses in a shift of like cross section. Thus, the sandbed could be used for solving for torsional stresses.

Consider FIGURE 7 now, and think of the sandbed as representing the cross section of a lamination carrying alternating magnetic flux: the flux lines within the lamination would be orthogonal to the mapper's flow lines. Again, think of this sandbed as being a cross section of a rectangular tube, carrying fluid in streamline flow: the isovelocity lines of the flow would be orthogonal to the sandbed mapper flow lines.[3]

(12) *Three-Dimensional Work*

Going beyond the two-dimensional fluid mappers described in this paper, be it said that, sometimes, three-dimensional mappers can be built for fields having axial symmetry.[3] Such mappers are, of course, more difficult to build. The slab or sandbed surface must be slightly curved, so that the flow-space thickness varies in terms of the radius. There are two types:[3] In the pro-axis type, the fluid flow is along the axis; in the cross-axis type, it crosses the axis. The flow spacing must vary directly with the cube root of the radius in the pro-axis type and, inversely, with the cube root of the radius in the cross-axis type.

These fluid mapper patterns also are subject to completion procedures, whereby simple graphic and arithmetic techniques bring about the complete solution of the field problem.

One company which has considerable use for three-dimensional fluid mappers has designed and made up metal molds for casting large slabs of both types. The mold surfaces are accurately curved, so as to give the cast slabs their proper curvatures and flow spacings.

(13) *Solution of Field Problems*

Whenever a fluid mapper establishes the field conformation, it is possible to photograph or otherwise record the pattern, and then turn it into a complete solution.[7] This procedure typically calls for selecting particular tubes, mapping the tubes in terms of curvilinear squares, and then going on to do whatever else is necessary to achieve numerical results. Such completion work involves nothing more than the application of graphical and arithmetical routines. A student's understanding of field phenomena is greatly enhanced by doing some of this work, quite irrespective of the training he may already have had in field theory.

Field problems are solved, of course, by a variety of methods. In the relatively small number of cases that are simple enough to yield to mathematics, mathematical attack may be the method of choice. It takes only a little complication, however, such as the imposing of an irregular boundary, or the introduction of a second medium, to put the problem outside the limits of practical mathematical solution.

These more difficult problems must then be handled by the use of graphical field mapping, equivalent networks, or the relaxation method; or by use of the electrolytic tank analog, the conducting paper analog, or the fluid mapper analog. The method of choice depends greatly on the actual nature of the problem, on the facilities available, and on the background and training of the individuals bearing the responsibility. There is no one best way to solve all field problems, and there never will be. We need all of the methods we now have, and more besides.

(14) *Fluid Mapper Uses*

Many textbooks not primarily devoted to fields nevertheless try to help the student by including some qualitative field sketches. A common example is a sketch of the resultant flux conformation in the case when a current-carrying conductor crosses a magnetic field. The sketch is included to aid the student in seeing why there is a force on the conductor. In many books, this sketch is drawn so that the flux lines bulge away from both sides of the conductor, much as the grain of a pine board would be separated if a nail is driven into the board. Such sketches, being sadly wrong, may do more harm than good. Actually, of course, the field bulges away on one side, but sinks in toward the conductor on the other side. Textbooks commonly in use show many examples of erroneous field sketches. The use of some elementary fluid mappers will, it is hoped, gradually eliminate such atrocities from our literature.

Beyond that, there are large possibilities for enhancing the student's understanding of fields, and his "feel" for them, by illustrating the books with appropriate fluid mapper pattern reproductions. One such book,[8] *Introduction to Electric Fields*, by Walter E. Rogers, has already appeared, illustrated in part by such pictures. The writer wishes to take this opportunity to mention the pleasure he derived from working with this author and supplying him with the patterns desired.

Wherever students are learning about potential fields, their insight and understanding of field phenomena may be much enhanced by at least looking at fluid mapper pictures and discussing them. Better yet, some problem solving by way of starting with fluid mapper patterns and completing the analysis to get numerical results can also be included. Still better, a modest fluid mapper laboratory can be established at a very moderate cost, where slab casting and fluid mapper operation can be demonstrated. The colleges are increasingly including such work somewhere in their teaching schedules.

Many teachers are so used to reaching for some instruments on the shelf and quickly setting up a demonstration, with available apparatus, that they may shy away from the business of learning to cast and finish plaster slabs during a demonstration. This procedure need be no deterrent. Slabs can be made up in advance and kept, dry, for indefinite periods. Soaking a slab for a half-hour or less makes it ready for demonstration. Small, thin slabs may need only a ten-minute soak.

Beyond these uses for fluid mappers in teaching and learning, a broad field of application to specific problems may be opened up. Here, of course, fluid mappers are in competition with other methods, and properly so. Fluid mappers do have the great advantage of showing, at once, what the field is like—an advantage offered by no other method. Furthermore, sandbed types of fluid mappers may in some cases be able to portray and to lead to the solution of certain distributed-source fields, and do it without competition, no other ready means of solution being available.

The writer developed fluid mappers primarily for their use as analogs for potential fields. However, it was quickly realized by people interested in fluid flow itself, that the techniques devised for making fluid mappers can be directly applied to portray streamline fluid flow in many other cases of interest. Considerable use has been made of fluid mappers for this "direct" or non-analogous purpose.

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CONCLUDING REMARKS

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"Is There a Science of Instrumentation?" E. U. Condon, in a paper of this title[1] provides the affirmative answer: ". . . in modern complex instruments a large part of the instrument is independent of the nature of the quantity to be measured. It is this fact that is giving rise to the recognition that there is a science of instrumentation concerned with these common elements and their systematic study and improvement. It seems quite likely that the instrument scientist will in the future play a role of steadily increasing importance in the development of all the sciences. It is a profession that should lend itself to specialization, and workers in all fields should be relieved as much as possible from the distraction of having to devote too much attention to the detailed design of instruments for their particular needs."

The Conference on Instrumentation on which this monograph is based was organized around this fundamental theme. We have examined some of the objectives and underlying principles of this new science of instrumentation. We have seen how the instrument designer, using generalized design principles, converts the specific requirements of a particular problem into an instrument to satisfy these requirements. We have learned the basis upon which transducers are selected to transform the physical quantity under study into another, more easily measured property. Many examples illustrating these points are presented in this monograph.

Considerable attention has been devoted to a major problem encountered in the design of instruments. This problem concerns the drawing up of instrument requirements and specifications by the research scientist in a quantitative form and in a technical language that can be understood by the instrumentation scientist. This difficulty is particularly aggravated in the fields of biology and medicine, where the variables that should be controlled often are not apparent, and therefore detailed requirements remain unknown or unavailable. The speakers have summarized instrumentation requirements in several fields in appropriate instrumentation "language."

Practical methods of securing liaison between research and instrumentation scientists have been tried at a few governmental, industrial, and institutional centers. We have heard description of the methods in use at representative centers and results obtained through these methods.

Several specific examples of analog methods were chosen to illustrate the techniques of translating instrumentation methods from one field of science to another, and to demonstrate the ability of the science of instrumentation to serve the various fields of science. These examples give concrete evidence of the value and potentialities of the generalized approach provided by instrumentation. These examples, to quote Condon[1] ". . . not only indicate the need for wide dissemination of information among the fields of science but reinforce the concept that instrumentation is a science in its own right. There is no reason why the practitioner of this science, conceived of as the logical approach to measurement problems, cannot provide measurement devices of a given type for a variety of fields. Certainly this would save the experimentalist much time and effort."

It is with this "need for dissemination of information among the fields of science" that this monograph is particularly concerned. Indeed, we shall have fallen far short of our objectives if the results of the conference on which this monograph is based are confined to the descriptive aspects of the material presented, valuable though these phases may be.

It is evident from these papers that the instrumentation approach to research problems is very useful. It is also obvious that an acute need exists for a means of interchanging information between research scientists in various fields and instrumentation scientists, if advantage is to be taken of this approach. The fact remains that there is no presently existing formal means whereby research scientists can submit instrumentation requirements and hope to secure information or advice on methods or devices available from other fields which may be applicable to their problems.

It is our hope that this publication will serve to stimulate thought and further discussion concerning ways of achieving this interchange. Whether such a need can best be supplied through a formal advisory group under the auspices of organizations such as our New York Academy of Sciences or, jointly, with the professional societies, or under an appropriate governmental agency, or through a new organization specifically formed for this purpose is a subject that requires further consideration and action. If we have encouraged such discussion and, especially, if such discussion leads to the establishment of a practical liaison between research and instrumentation scientists, then these papers will have attained their primary objective.

Reference

1. Condon, E. U. 1949. Science. **110:** 339–342.

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